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OXYGEN BOOSTING OF AN AIRCRAFT-ENGINE CYLINDER IN CONJUNCTION WITH INTERNAL COOLANTS

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OXYGEN BOOSTING OF AN AIRCRAFT-ENGINE CYLIXDER IN CONJUNCTION WITH INTERNAL COOLANTS

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SUMMARY

Object. - To determine the possibility of attaining or approaching critical-altitude power at altitudes considerably higher. than the critical as limited by the supercharger by the use of oxygen in conjunction with internal coolants.

Scope. - Full-scale single-cylinder tests were made to determine: (1) the knock-limited or temperature-limited power attainable by the use of oxygen, both with and without internal coolants; and (2) the relative values of four internal coolants: ammonium hydroxide, methyl alcohol, a mixture of 70 percent methyl alcohol and 30 percent water, and a mixture of 80 percent ethyl alcohol and 20 percent water.

Summary of results. -

1. Data obtained in full-scale single-cylinder-engine tests indicate that it may be possible to attain critical-altitude power at altitudes at least 10,000 feet higher than the critical altitude as limited by the engine supercharger.

2. Although some differences were apparent in the effectiveness of the four internal coolants, the differences were not, important. In the application to multicylinder engines the choice of coolant will probably be determined by a practical consideration, such as availability.

3. Temperature limitations to the use of oxygen were overcome by the use of high fuel-air ratios in conjunction with internal coolants.

Conclusion. - The use of oxygen in conjunction with a suitable internal coolant affords a means of obtaining operation for short periods of time at or near critical-altitude power and at altitudes considerably higher than the critical altitude as limited by the supercharger.

INTRODUCTION

The problem of attaining high power outputs at altitude has been chiefly related to engine-supercharger performance although instances have been reported of attempts to supercharge the engine by addition of oxygen to the normal intake air.

The idea of carrying a sufficient supply of oxygen for a relatively short burst of high power, when an aircraft is being operated at altitudes above the critical altitude, at first appears to offer very interesting possibilities for combat. Disadvantages that must be overcome are, however, inherent in the procedure. The use of an intake gas very rich in oxygen leads to high combustion-gas temperatures with consequent overheating and tendency to preignite or knock. This tendency can be partly overcome by drastic increase of the fuel-oxygen ratio. The response to this enrichment is limited and some means must be employed to increase the internal cooling if any important increases in power are to be obtained. Water with or without a freezing-point depressant provides such an internal coolant.

The use of water and water-alcohol mixtures introduced with the intake air as knock inhibitors and as internal coolants is not new. It was mentioned in a speech by Ford L. Prescott before the SAE International Automotive Engineering Congress in Chicago in 1933. (See also references 1 to 4.) As far as is known, however, the combination of oxygen boosting and internal cooling has not heretofore been attempted. The series of tests described in this report was laid out to determine the applicability of the internal-cooling principle in conjunction with oxygen boosting at low manifold pressures. The program for these tests was designed (1) to determine the effect on engine operation of increasing the oxygen content of the intake air and of adding internal coolant, and (2) to determine whether the engine power could be sufficiently increased by oxygen addition to make the method of interest to the military services. The tests were conducted during the fall of 1942 at the Langley Memorial Aeronautical Laboratory, Langley Field, Va.

APPARATUS AND TEST METHODS

The tests were carried out with a Wright 1820 G200 (C9GC) cylinder mounted on a CUE crankcase. This cylinder has a $6\frac{1}{8}$-inch bore and a $6\frac{7}{8}$-inch stroke. The internal-coolant system consisted of a pressure tank for the coolant, a calibrated rotameter, and a spray nozzle with self-contained needle valve. The coolant was sprayed downstream into the intake pipe and the spray was continuous rather than timed with the engine intake stroke.

Oxygen was supplied from a battery of six commercial 200-cubic-foot cylinders. In order to reduce the oxygen pressure to about 150 pounds per square inch gage, the high-pressure gas was first sent through a commercial reducing valve such as is used with welding outfits. The oxygen was then sent through an accurate pressure-regulating valve, which was controlled by air loading from a reducing valve on the engine-control bench, From the regulating valve the oxygen was passed through a measuring orifice, then through a hand-operated throttle valve to the intake system of the engine. The inlet air was sufficiently heated that, after the coli oxygen was admitted, the final temperature of the gas mixture was 250° F. The oxygen was admitted through a diffuser to the intake system upstream from the thermometer that measured the temperature of the intake air.

Engine conditions were as follows:

Engine speed, rpm	2000 and 2500
Compression ratio	7.0
Inlet-air temperature (after introduction of oxygen but before introduction of fuel or coolant), °F	250
Spark advance (both plugs), degrees B.T.C.	20
Cooling-air pressure drop across cowling, inches of water	10 and 20
Cooling-air inlet temperature, °F	110 and 125

3-2 reference fuel was used for the preliminary tests at 2000 rpm, and standard Army 100-octane aviation gasoline, obtained in one lot from the Army supply at Langley Field, was used for the other tests.

The coolants used were commercial ammonium hydroxide (NH_4OH) having a specific gravity of about 0.90, technical methyl alcohol (CH_3OH), a mixture of 70 percent commercial methyl. alcohol and

30 percent water, and a mixture of 80 percent ethyl alcohol (C_2H_5OH) and 20 percent water. Percentage was by volume. Water was not used alone in the present tests because preliminary tests on a CFR engine had indicated that water alone was not so effective as the other coolants. Other unpublished NACA results have indicated that the rich-mixture response with water is poorer than with any of the other coolants used.

Knock was determined by means of an oscillograph with a Stancal detonation pick-up unit in the engine. Temperatures were measured by iron-constantan thermocouples and a potentiometer. Champion C34S spark plugs were used.

Because of the unusual nature of the tests and because of the difficulty of making accurate determinations of the point of light or incipient knock when oxygen was being added to the intake air, it was necessary that the operators be experienced and that they exercise good judgment in determining the actual knock points. It was found, however, that each of the two crews running the tests could check data obtained by the other with very acceptable accuracy; it is believed, therefore, that the data presented are sound.

Tests were made for surface ignition by momentarily cutting the ignition switch. The maximum permissible engine performance was limited either by knock, by afterfiring, or by a barrel temperature of 325° F, measured at the middle of the rear of the barrel.

Two means were employed to vary the oxygen intake to the engine: (1) constant oxygen percentage and varying manifold pressure, and (2) constant manifold pressure and varying oxygen percentage. For both methods, the limits were determined over the usable range of fuel-air ratio or fuel-oxygen ratio. For the first tests, the proportion of oxygen in the intake air was held constant for each curve and the knock or temperature limit was attained by varying the manifold pressure. Coolant was added in the proportion of 50 percent of the fuel weight. Holding a constant percentage of oxygen in the intake air involved resetting the oxygen flow each time the intake air pressure (and, hence, the air flow) was changed but, in view of the fact that the data were more conventional and thus more easily interpreted in that form, it was believed worth while to obtain at least one set of data in that manner.

The manifold pressure was then held constant and oxygen was added. Such a procedure was very satisfactory both for the comparison of coolants and for the determination of the effects of varying amounts of coolant. The method had the advantage of simplicity. Two sets of tests using this method were run. One set was conducted to determine whether critical-altitude power could be maintained by keeping the rate of induction of the total gaseous oxygen constant irrespective of the total gas that entered the cylinder. Tests were run with normal air at an inlet pressure of 44 inches of mercury absolute and at an inlet pressure of 28.5 inches of mercury absolute. The mass rate of oxygen flow was maintained at the same value for both pressures. Coolant was added to prevent knock or temperature limitations, and the data were not limited except at the lean end of the range of fuel-air ratio. The other set of tests in which the manifold pressure was held constant was conducted to compare the effectiveness of the different coolants and to determine how great an addition of coolant could be used to advantage. These tests were knock-limited or temperature-limited throughout the range of fuel-oxygen ratio. The procedure was to set the manifold pressure at a predetermined value, to set the fuel flow at some value that would give a lean mixture, and then to add oxygen until knock or temperature limitation was encountered. The fuel flow was then increased and more oxygen was added until the knock or temperature limit was again reached, and so on.

In addition to the power tests, a short series of tests was conducted to determine the amount of extra coolant that could be tolerated when coolant was added without increasing the oxygen intake. These tests were carried out by determining the amount of coolant required to cause a 10-percent drop in engine power when no additional oxygen was added.

Results of the preliminary tests at 2000 rpm are plotted on the basis of "equivalent fuel-air ratio," that is, the fuel-air ratio computed by dividing the fuel weight by the air weight that would have had to be inducted to furnish all the gaseous oxygen inducted. Such a method, though somewhat unusual, has the advantage of putting the data in a form that is more commonly used.

Results of the tests at 2500 rpm are plotted on the basis of fuel-oxygen ratio, in which the fuel weight is divided by the weight of oxygen inducted. In no case was the coolant considered in computing the fuel-air or fuel-oxygen ratio, although combustible material was present in all the coolants used.

Engine power was absorbed by an electric dynamometer. The ratio of coolant to fuel or coolant to oxygen was set by a calibrated rotameter. Fuel consumption was measured by a burette, a stopwatch, and a revolution counter.

EXPERIMENTAL RESULTS

Tests at Constant Oxygen Percentages

Results of the first tests with S-2 fuel at 2030 rpm are shown in figure 1. The internal coolant was ammonium hydroxide added in the proportion of 50 percent of the fuel weight. Because of the difficulty of keeping the oxygen flow adjusted to the correct percentage of the total gas flow during these tests, scatter of the points occurred but the trends and general relationships of the curves are unmistakable.

The addition of ammonium hydroxide in the amount of 50 percent of the fuel inducted raised the permissible indicated mean effective pressure at a fuel-air ratio of 0.10 from 194 pounds per square inch without coolant to 276 pounds per square inch with coolant and with normal air supercharging (23.2 percent oxygen by weight). Subsequent progressive enrichment of the air by increasing the oxygen content resulted in progressive decrease in the maximum permissible power, as shown by the family of curves until, with a total oxygen concentration of 33.6 percent, the permissible power when using ammonium hydroxide was lower at a fuel-air ratio of 0.10 than the permissible power with no coolant and with normal air supercharging. The important feature of the data as shown is the rather considerable increase in power for any one manifold pressure as the oxygen concentration is increased. At a manifold pressure of 30 inches of mercury absolute, for instance, the normal air boost gave an indicated mean effective pressure of about 144 pounds per square inch (points A). With ammonium hydroxide aid with the oxygen concentration increased to 38.6 percent, the indicated mean effective pressure at a manifold pressure of 30 inches of mercury absolute was increased to about 208 pounds per square inch (points B). Intermediate oxygen concentrations increased the power approximately in proportion to these values.

Tentative performance estimates can be made from the data shown in figure 1 in conjunction with figure 2, which shows the indicated specific additive oxygen consumption. Examination of figure 1 shows that the engine was developing an indicated mean effective pressure of about 212 pounds per square inch at a manifold pressure of 45 inches of mercury absolute (points C), Then, with tine oxygen content of the air increased to 38.6 percent, the engine developed an indicated mean effective pressure of about. 2G8 pounds per square inch at a manifold pressure of 30 inches of mercury absolute (points B). The indicated specific fuel consumption with the oxygen boost was 0.81 pound per horsepower-hour, which corresponds to an indicated specific ammonium hydroxide consumption of about 0.41 pound per horsepower-hour; the indicated specific additive cxygen consumption (fig. 2, point B) was about 0.78 pound per horsepower-hour; the total fluid per indicated horsepower-hour of material in addition to fuel therefore amounted to 1.19 pounds. This value represents thr additional weight, exclusive of fuel, required to maintain the power normally attainable at a. manifold pressure of 45 inches of mercury absolute when only 30 inches can be maintained by the supercharger.

The horsepower corresponding to point B is 106, or 954 indicated horsepower, for the nine-cylinder engine. At the rate of 1.19 pounds per horsepower-hour, a 10-minute spurt at this power would require 189 pounds of oxygen and interrial coolant in addition to the fuel.

Tests for Maintenance of Critical-Altitude Power

The data shown in figures 3 and 4 were obtained during tests conducted to deternine whether critical-altitude power could be maintained by keeping the rate of total gaseous-oxygen induction constant irrespective of the total gas entering the cylinder. The characteristics of one of the typical Unite3 States pursuit airplanes were used for convenience in determining the test conditions. This particular airplane was rated at a manifold pressure of 44 inches of mercury absolute at its critical altitude. At 10,000 feet higher than its critical altitude as limited by the supercharger, the same airplane could maintain a manifold pressure of 28.5 inches of mercury absolute. Figures 3 and 4 show performance curves at constant manifold pressures of 44 inches of mercury absolute (corresponding to the critical altitude of the airplane as limited by the supercharger) and 28.5 inches of mercury absolute (corresponding to 10,000 ft higher than the critical altitude). For these tests the fuel-oxygen ratio was varied from that giving knock or temperature limit on the lean end to that giving irregular operation at the rich rnd. The intake gas at the manifold pressure of 44 inches of mercury absolute was ordinary air and, at the manifold pressure of 28.5 inches of mercury absolute, the air was enriched with oxygen until the total gaseous-oxygen consumption was the same as it was at a pressure of 44 inches of. mercury absolute and with ordinary air; that is, cxygen was inducted at the same rate at both manifold pressures.

The weight of coolant for these tests was determined by the amount of additive oxygen rather than by the fuel quantity. This procedure would be the logical one to follow in practice because the amount of coolant required depends, of course, largely upon the amount of additive oxygen entering the cylinder. In thsse tests, inasmuch as the additive oxygen flow was constant, the test procedure was greatly simplified by keeping a constant rstio of coolant to oxygen rather than by attempting to vary the coclant as the fuel flow was varied. Two different coolants were used for these tests, namely, ammonium hydroxide and a mixture of 70 percent methyl alcohol and 30 percerit water. Coolant was added in the prcportions of 50, 65, ind 75 percent by weight of the oxygen flow.

The results when ammonium hydroxide was used as the coolant are plotted in figure 3. It is seen that the engine power was easily maintsined by use of the oxygen and the internal coolant. Tne use of additive oxygen and internal coclant at a manifold pressure of 28.5 inches of mercury absolute actually increased the power slightly as compared with air at a manifold pressure of 44 inches of mercury absolute. At the left-hand end of the curves the linitaticn was knock or temperature and at the right-hand end the limitation was irregular running.

With coolant-oxygen ratios of 65 and 75 percent, the mixture could be leaned to a fuel-oxygen ratio of 0.37 before knock or temperature limit was encountered. For the curve with a coolant-oxygen ratio of 50 percent, the mixture could be leaned to a fuel-oxygen ratio of about 0.415, where engine operation was limited by both knock and barrel temperature.

Figure 4 shows the engine performance when the coolant was a mixture of 70 percent methyl alcohol and 30 percent water. All curves were limited by knock at a fuel-oxygen ratio of about 0.40 to 0.45. The fact that the engine could be operated somewhat leaner when ammonium hydroxide was the coolant than was possible when the 70-30 mixture of methyl alcohol and water was the coolant indicates that the ammonium hydroxide was the better coolant and knock inhibitor, The relative values of the different coolants actually vary somewhat with engine conditions, particularly with fuel-air ratin. Unpublished NACA data show that, for air-boosted operation, either the 70-30 mixture of methyl alcohol and water or 100 percent methyl alcohol used as a coolant will allow best performance in the very rich-mixture region but that water and ammonium hydroxide allow better performance in the lean-mixture region.

Comparison of Different Coolants

An investigation was next made to determine the effectiveness of the four internal coolants, These tests were carried out at constant manifold pressure. As the oxygen percentage in the intake gas was increased, the knocking tendency increased and the knock limit was reached. Increase of oxygen percentage at constant manifold pressure has an effect similar to increase of manifold pressure at constant oxygen percentage.

Figure 5 shows the engine performance at a manifold pressure of 20 inches of mercury absolute for operation with no coolant and with ammonium hydroxide, methyl alcohol, a 70-30 mixture of methyl alcohol and water, and an 80-20 mixture of ethyl alcohol and water. The coolants were added in the proportion of 100 percent of the fuel weight, The data on indicated mean effective pressure show a slight ads-antage in favor of ammonium hydroxide and the mixture of ethyl alcohol and water. The specific oxygen consumption and the specific liquid consumptions are shown in figure 6.

In figure 7 the permissible oxygen percentages for the data of figure 5 are plotted against fuel-oxygen ratio for the runs at constant manifold pressure. The percentage of oxygen in the air at constant manifold pressure has somewhat the same significance as the curve of maximum permissible manifold pressure at constant oxygen concentration,

In figure 8, some of the representative engine temperatures are plotted against indicated mean effective pressure. In the interpretation of these data, it is important to keep in mind the fact that each point on a curve represents a different fuel-oxygen ratio. The curve of the temperature at the center of the head between the valves for air-boosttd operation illustrates this fact. The loop at the left-hand end of the curve is due to the temperature trends that occurred between extremely lean operation and operation at minimum permissible indicated mean effective pressure, The point in figure 8 at an indicated mean effective pressure of about 163 pounds per square inch and 410° F is the temperature corresponding to the leanest point on the performance curve. From this point of extremely lean operation the permissible indicated mean effective pressure then decreased as the mixture was enriched; the temperature gradually increased, As the point of minimum permissible indicated mean effective pressure was passed, the temperature continued to rise for a short time as the power increased; then, with further increase in indicated mean effective pressure, the temperature decreased because of the enrichment of the fuel-oxygen mixture. Near the end of the curve the temperature dropped rapidly and the power started to peak because of the extreme enrichment. The curve of indicated mean effective pressure against fuel-air ratio corresponding to the data of figure 8 is shown in figure 5.

The temperatures with coolant and oxygen show very steep rates of decrease as the mixture is enriched; at the high power outputs that are permitted by rich mixtures, therefore, the engine temperatures are low. Some of the recorded temperatures of the center of the head between the valves, for example, were below the boiling point of water. It must be noted, however, that the head temperatures at the lower permissible power levels (thst is, at the leaner mixtures) are, in general, decidedly higher than at normal air boosting.

Figures 9 to 12 show the engine performance when the manifold pressure was raised to 30 inches of mercury absolute with the same coolants as for figures 5 to 8. The mixture of ethyl alcohol and water apparently permitted higher indicated mean effective pressure than did the other coolants, as is shown in figure 9. The ethyl-alcohol data were taken with a new cylinder on the engine, and it is believed that the higher performance permitted by the ethyl alcohol should therefore be discounted. In any case, the differences shown are not large enough to be important.

The same general trends are to be seen in figures 9 to 12 as were observed in figures 5 to 8 with the exception that the permissible percentage of oxygen in the air was decidedly lower than at a manifold pressure of 20 inches of mercury absolute.

Effect of Different Percentages of Coolant

Following the tests with different coolants, a series of tests was made in which the amount of coolant was equal to 50, 100, and 150 percent of the fuel flow. The mixture of 70 percent methyl alcohol and 30 percent water was selected as probably being of most interest because of its availability in quantity. Manifold pressure was 20 inches of mercury absolute. The indicated mean effective pressures and the fuel consumptions are plotted in figure 13, and figure 14 shows the specific liquid consumptions and the specific total oxygen consumptions. Engine performance at a coolant flow of 150 percent was somewhat unsteady and it was therefore concluded that the proportion of 103-percent coolant to fuel probably should not be exceeded.

Temperature trends and the percentage of oxygen permitted in the intake air are shown in figures 15 and 16. These curves are similar to previous figures.

When oxygen is added to the intake air, the air consumption of the engine (measured prior to introduction of oxygen) is, of course, reduced. Specific air consumptions for the tests with varying percentages of internal coolant are given in figure 17. It should be kept in mind that increasing the percentage of internal coolant increases the permissible oxygen addition. Enriching the fuel-gas mixture also increases the permissible oxygen addition. If these two facts are borne in mind, the trends shown in figure 17 are more easily understood. For convenience, some of the percentages of oxygen in the inlet air are noted on the curves of figure 17. At the highest outputs, where the concentration of oxygen in the air was approximately 70 percent (fig. 15), the specific air consumption was as low as 1 pound per indicated horsepower-hour.

Combustibility Limitations

The design of apparatus for inducting oxygen, coolant, and an increased quantity of fuel into the engine will necessarily require that all three materials start flowing into the induction system at nearly the same time. If oxygen starts flowing before the coolant starts, severe knock may result. On the other hand, there may be some question as to the effect on the engine operation if the coolant and additional fuel start flowing before the oxygen starts. With this question in mind, a brief series of tests was carried out to see how much coolant could be added at various fuel-oxygen ratios without causing the engine to lose power excessively. A power loss of 10 percent was arbitrarily selected as the maximum that could be tolerated for a few seconds of operation. In figure 18 the coolant-fuel ratio necessary to cause a power loss of 10 percent is plotted against fuel-oxygen ratio. Data are shown for ammonium hydroxide and for the 70-30 mixture of methyl alcohol and water at manifold pressures of 35 and 50 inches of mercury absolute. It is seen that a very considerable addition of coolant can be tolerated at the lean mixtures but that the allowable amount of coolant decreases as the mixture is enriched. At the richest mixtures the allowable amount approaches zero. This effect occurs, however, in a region already bordering upon unsteady operation. Differences in the amounts of coolant that could bo tolerated at different manifold pressures are probably of small significance, but it does appear that the methyl alcohol had less choking effect on the engine than did the ammonium hydroxide at either manifold pressure,

DISCUSSION

The data presented herein show that it is possible to obtain very considerable increases in engine power at relatively low manifold pressures by the use of oxygen boost in conjunction with an internal coolant. Details of the application are dependent upon the individual requirements of the engine and upon the installation. Certain features of engine operation with oxygen boost, however, are probably universally applicable and will be outlined briefly in this section,

Charging efficiency, - It was shown in figure 17 that the air consumption decreased decidedly as more oxygen was added. For the tests reported herein, the additive oxygen was raised to tte same temperature as the inlet air, It is obvious that there is no point in heating the oxygen introduced into a service engine because in a service engine, if the oxygen were introduced cold rather than hot, the engine would induct more air. Without any increase in the amount of coolant, therefore, the permissible power would be higher because of the lower percentage of oxygen in the charge and the lower temperature of the air, Injection of liquid oxygen would further improve the charging efficiency but might cause icing difficulties, Estimates of the effects of oxygen addition on the cooling and on the total quantity of oxygen inducted are given in the appendix.

Heating tendencies. - First. consideration of the conditions encountered during oxygen boosting leads directly to the conclusion that, because of the lack of inert gas to act as a thermal cushion, the combustion chamber and the parts of the engine in contact with the flame must necessarily run hotter than they would with normal air boost, It would be expected, therefore, that operation with oxygen boost would be beset with preignition difficulties caused by local hot spots within the cylinder, Experience with the wide variety of engine conditions used during the tests has shown that the preignition danger is real if the oxygen addition is not properly handled.

If internal coolant is used, however, and the fuel flow is increased until the over-all fuel-oxygen ratio is of the same order as is normally used under take-off conditions, the engine will run very cool. Figures 8, 12, and 16 show this effect. The cooling effect is strikingly shown in figure 12. The temperature of the center of the cylinder head between the valves, within 1/8 inch of the surface of the combustion chamber, was below the boiling point of water when the engine was davoloping an indicated mean effective pressure of 220 pounds per square inch.

Engine-operating characteristics. - The most noticeable characteristic of operation with oxygen anrichment was the immediate "evening-up" and steadiness of operation as soon as a small quantity of additiva oxygen was introduced into the inlet air. The range of combustibility was evidently widened appreciably by increasing the oxygen content of the inlet air. As more and more oxygen was added, engine operation became increasingly rough or hard-hitting. By "rough operation" is meant not irregular operation but very regular operation with each explosion decidedly accented. Because the explosions were very hard and almost metallic in sound, determination of knock by ear was exceedingly difficult. Judged by the diagram from the magnetostriction knock indicator, the rate of pressure rise was high. No mechanical troubles traceable to the use of oxygen or coolant were encountered other than a somewhat excessive rate of wear of the top piston rings.

DIFFICULTIES ANTICIPATED IN APPLICATION

Distribution. - It is obvious that, inasmuch as an excess of oxygen will cause heavy hock and an excess of coolant will cause loss of power, the materials must be well distributed to the different cylinders; otherwise, some cylinders might be flooded and others might knock violently.

Metering. - The additive materials must be properly metered if satisfactory operation is to be maintained. It is possible to construct apparatus so balanced that it will deliver coolant, fuel, and oxygen in proper proportions to maintain critical-altitude power to, say, 10,000 feet highar than the critical altitude as limited by the supercharger.

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APPENDIX

ESTIMATES ON EFFECTS OF OXYGEN ADDITION TO INLET AIR ON TOTAL QUANTITY OF OXYGEN INDUCTED

In connection with tests on the supercharging of engines by means of oxygen additions, it is necessary to know the effect of the oxygen additions on the air quantity inducted to the engine. Computations that provide estimates on this effect are given in the following three steps: (1) the temperature change of the inlet air is computed for various amounts of additive oxygen; (2) the density change of the inlet air at constant pressure is calculated by taking into account both the cooling effect of the oxygen as determined in step (1) and the displacement of air by the oxygen; (3) the actual increase in oxygen inducted into the engine is calculated by taking into account the effects determined through steps (1) and (2). Throughout the calculations it is considered that the total pressure and the volume rate cf flow of the inlet-gas mixture remain constant. In the discussion, the air after oxygen addition but not including the added oxygen will be referred to as the "final" air; the air, when no oxygen is being added, will be referred to as the "initial" air. The oxygen will be considered to be introduced into the air at the following conditions; (a) as a gas at the same temperature as the inlet air; (b) as a gas at the boiling temperature of the oxygen at atmospheric pressure, -297° F; and (c) as a liquid at the boiling temperature of oxygen. These three conditions represent the two probable extreme conditions, (a) and (c), and a possible intermediate condition (b).

The temperature drop of the air will first be estimated for (c). Let

M_a mass of final air

M_o mass of oxygen, exclusive of oxygen in the final air

T_a initial temperature of air

T_o initial temperature of oxygen

T_f final temperature of air and oxygen

L_o heat of vaporization of oxygen

c_{p_o} specific heat of oxygen at constmt pressure

c_{p_a} specific heat of air at constant pressure

then

$$T_a - T_f = M_o \left[\frac{L_o + c_{p_o}(T_a - T_o)}{\frac{M_o}{M_a} c_{p_o} + c_{p_a}}\right] \qquad (1)$$

For condition (b), the factor L_o is removed from equation (1). Then, let

$T_a = 212^\circ$ F

$T_o = -297^\circ$ F

L_o = 91.6 Btu per pound

$c_{p_o} = 0.22$ Btu per pound $^\circ$F

$c_{p_a} = 0.24$ Btu per pound $^\circ$F

Substitution of these values for the temperature drop in equation (1) for conditions (b) and (c) gives the results shown in figure 19. The increase in oxygen concentration by weight percentage is the ratio of the weight of the added oxygen to the weight of the oxygen in the final air in percentage.

The next step is the determination of the density changes of the air caused by the temperature changes and by the displacement of the air by oxygen.

Let

p_o partial pressure of oxygen, exclusive of oxygen in air

p_a partial pressure of final air

ρ_i density of initial air

ρ_f partial density of final air $\left(\frac{\text{mass of final air}}{\text{volume of final gas mixture}}\right)$

28.8 molecular weight of air

32.0 molecular weight of oxygen

Then

$$p_a = \frac{p_o}{0.90} \frac{M_a}{M_o} \tag{2}$$

since

$$\frac{28.8}{32.0} = 0.90$$

or

$$\frac{p_a}{p_o + p_a} = \frac{1}{0.90 \frac{M_o}{M_a} + 1} \tag{3}$$

The partial density of the final air inducted relative to the density of the initial air is proportional to the partial pressures and inversely proportional to the sbsolute temperatures. Therefore

$$\frac{\rho_f}{\rho_i} = \frac{p_a}{p_o + p_a} \times \frac{T_a + 460}{T_f + 460} = \frac{1}{0.90 \frac{M_o}{M_a} + 1} \times \frac{T_a + 460}{T_f + 460}$$

The quantity $\frac{\rho_f}{\rho_i}$ (the ordinate of fig, 20) is the density ratio of the final air to the initial air. Differences between the two densities, as previously stated, are caused by the temperature change from T_a to T_f and by the displacement of the initial air by oxygen. Figure 20 is calculated by solving for the densities under the different conditions. The abscissa of figure 20 is the percentage of the weight of added oxygen to the weight of oxygen in the final air.

The final step is to determine the actual increase in oxygen inducted into the engine. The abscissa of figure 21 is the ratio of the weight of added oxygen relative to the weight of inducted air without oxygen addition and the ordinate is the incaease in total oxygen intake by weight percentage. The ordinate is made up of two factors: (1) the change (caused by cooling and consequent increased density and by displacement of the initial air by additive oxygen and consequent decrease of the partial density of the air) in the amount of oxygen obtained from the sir; plus (2) the additive oxygen, corrected for density changes in the same manner as the air. This percentage increase in oxygen inducted is a measure of the power increase to be expected.

The use of figure 21 is illustrated by the following example: The air consumption of an engine is 6000 pounds per hour and it is desired to get a 66-percent increase in total oxygen inducted into the engine when liquid oxygen is used. The abscissa ccrresponding to a 66-percent increase of oxygen inducted, for liquid oxygen, is 0.14. The required rate of added liquid. oxygen is then 0.14 × 6000 or 840 pounds per hour. For the same total oxygen rate, 0.188 × 6000 or 1128 pounds per hour of additive gasecus oxygen at 212° F would be required.

An example will now be worked out to show how the curves of figures 19, 20, and 21 were obtained. With cxygen added as a liquid at -297° F, equation (1) reduces to

$$T_a - T_f = \frac{M_o}{M_a}\left(\frac{203.6}{0.24 + 0.22\,\frac{M_o}{M_a}}\right)$$

Assume that $M_o/M_a = 0.20$. Then $T_a - T_f = 143.5^\circ$ F.

The percentage increase in oxygtn is $\frac{0.20}{0.232} \times 100 = 86.2$.

One point for the upper curve of figure 19 is thus located with the abscissa at 86.2 and the ordinate at 143.5. If the example is now carried to figure 20, then

$$\frac{\rho_f}{\rho_i} = \left(\frac{1}{0.90\,\frac{M_o}{M_a} + 1}\right)\left(\frac{T_a + 460}{T_f + 460}\right) = \left(\frac{1}{0.90 \times 0.20 + 1}\right)\left(\frac{672}{529}\right) = 1.08$$

One point for the upper curve of figure 20 is then located with the abscissa at. 86.2 snd the ordinate at 1.08.

It is next desired to carry the example to figure 21. The abscissa of figure 21 is the value of M_o/M_a multiplied by the correction factor 1.08, or 0.20 × 1.08 = 0,216. This value is the weight of oxygen relative to the air mass that would have been taken in without the oxygen addition, The ordinate is the increase in the oxygen obtain-d from the air plus the added oxygen on a percentage basis, or:

$$(1.08 - 1)\ 100 + \left(\frac{0.216}{0.232}\right) 100 = 8 + 93 = 101 \text{ percent}$$

The data indicate that the cooling effect resulting from introducing the oxygen either as a liquid or as a gas at the boiling temperature is appreciable and results in a considerable increase in the total oxygen content inducted into the engine. For this reason the cooling effect of the oxygen should be used as far as possible because by so doing the power for a given weight of oxygen inducted is further increased.

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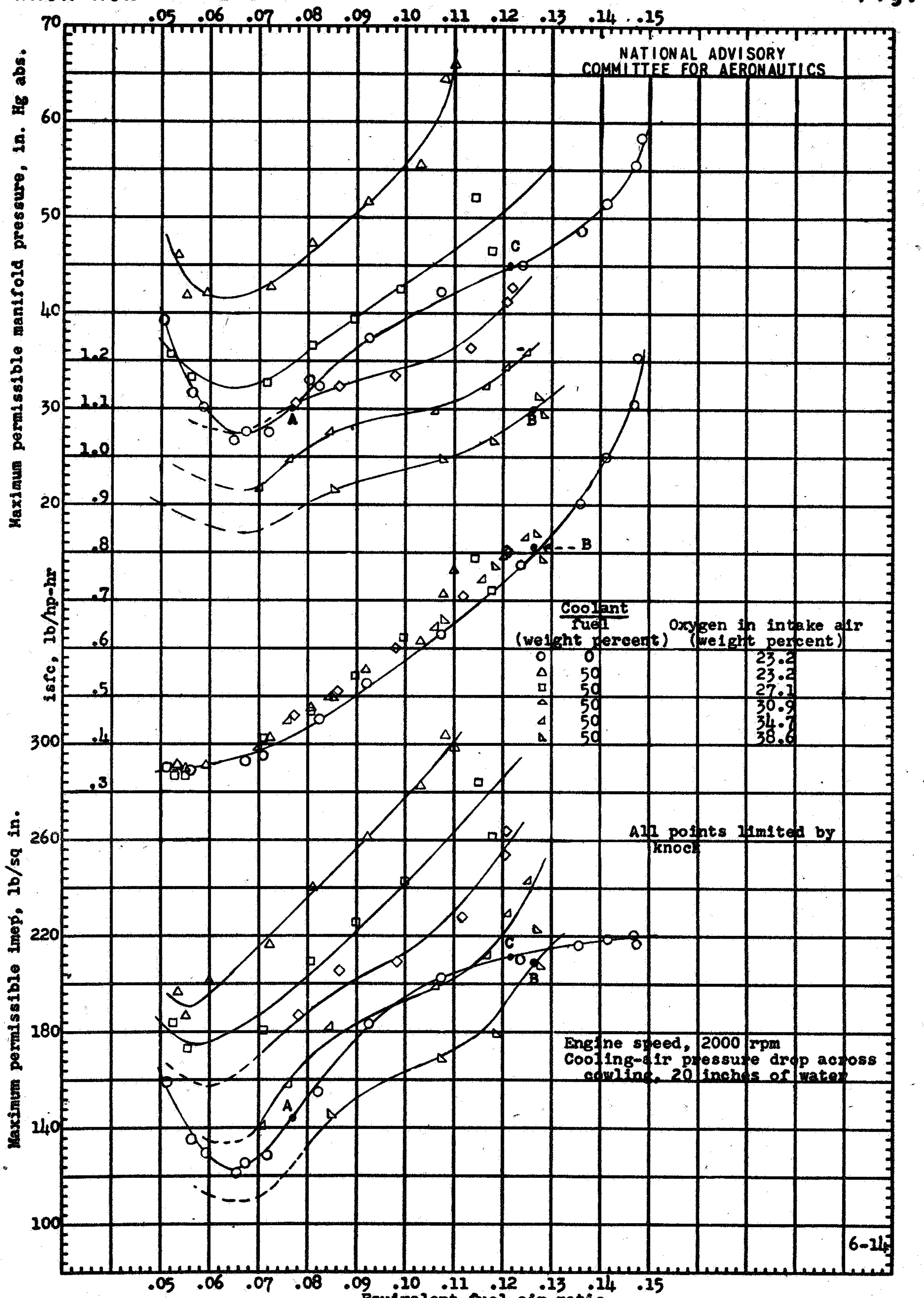

Figure 1. - Engine performance obtainable with various oxygen concentrations in nitrogen using 50 percent as much ammonium hydroxide as fuel. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2000 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 20 inches of water; cooling-air upstream temperature, 110° F; fuel, S-2.

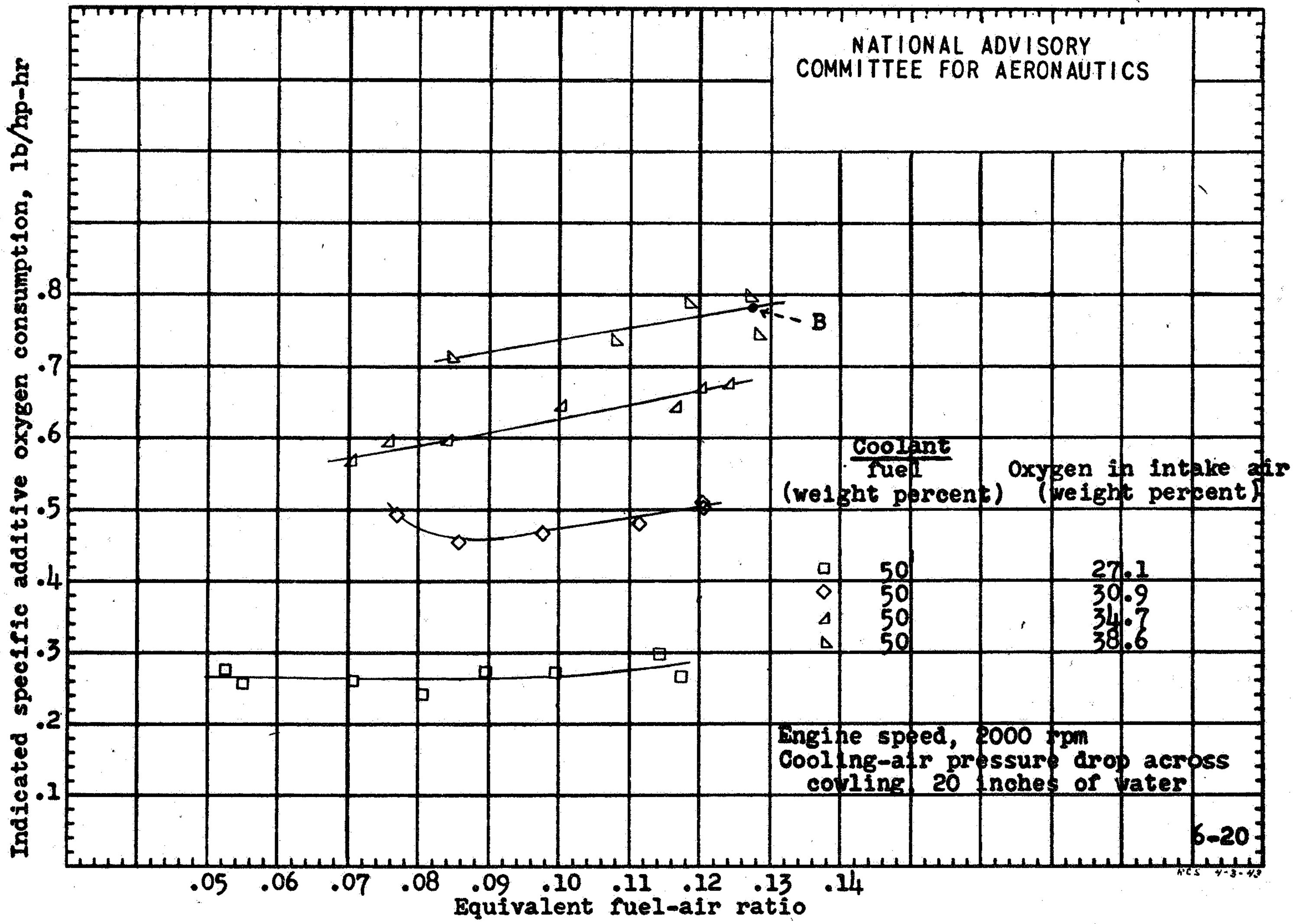

Figure 2. - Indicated specific additive oxygen consumption with various oxygen concentrations in nitrogen, using 50 percent as much ammonium hydroxide as fuel. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2000 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 20 inches of water; cooling-air upstream temperature, 110° F; fuel, S-2.

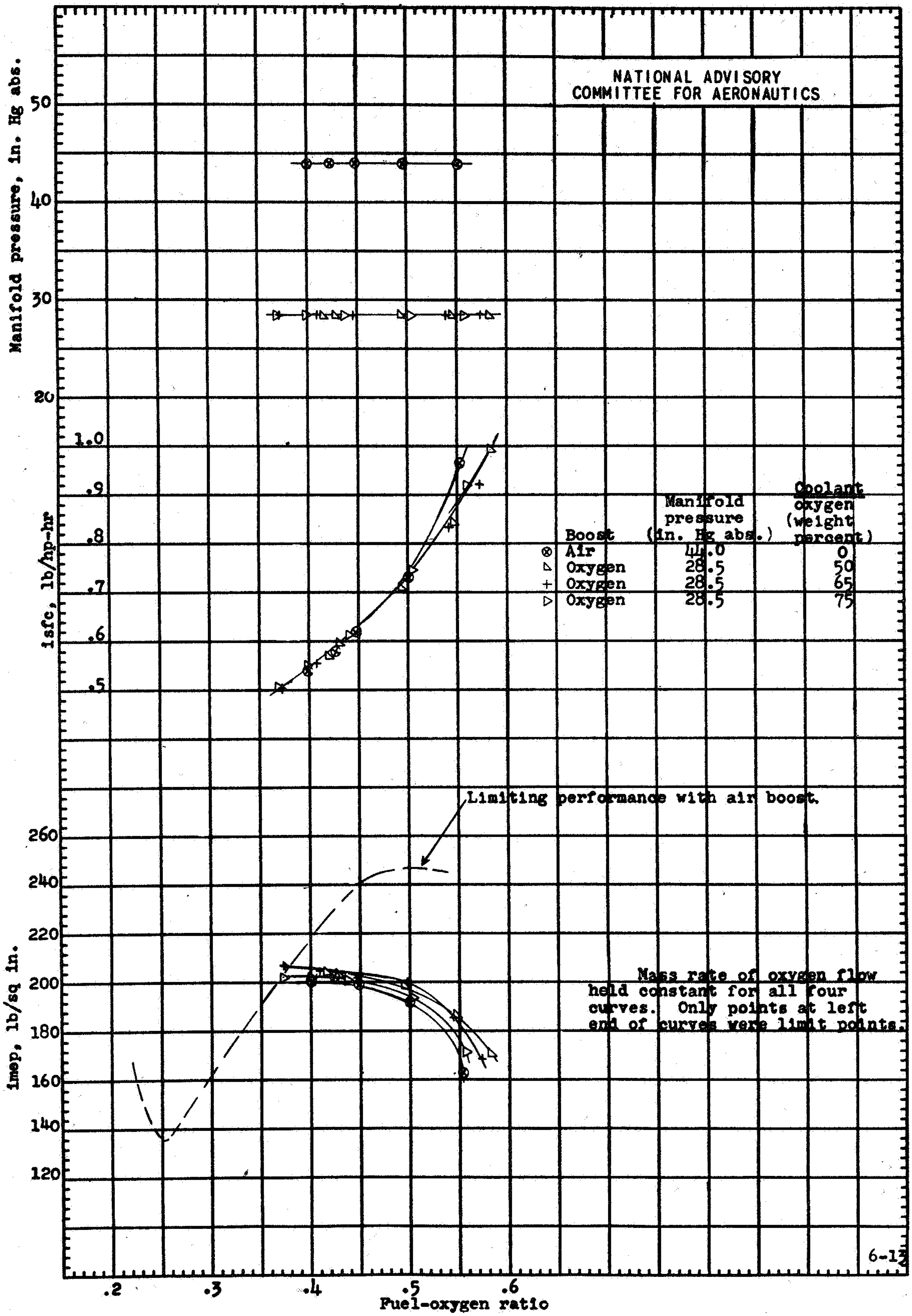

Figure 3. - Reproduction of critical-altitude performance at manifold pressure corresponding to 10,000 feet above critical altitude with ammonium hydroxide as internal coolant. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

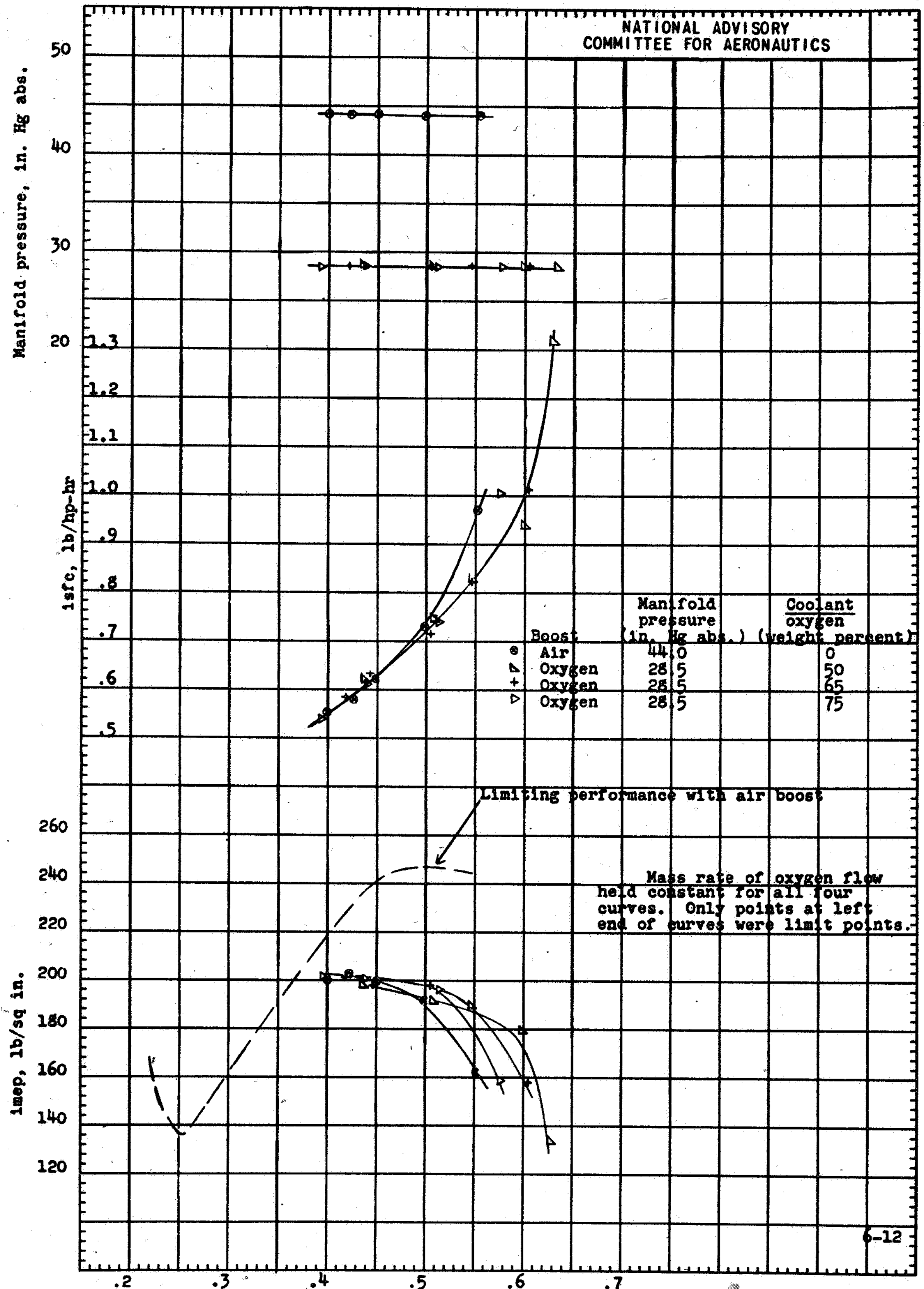

Figure 4. - Reproduction of critical-altitude performance at manifold pressure corresponding to 10,000 feet above critical altitude with 70 percent methyl alcohol and 30 percent water as internal coolant. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

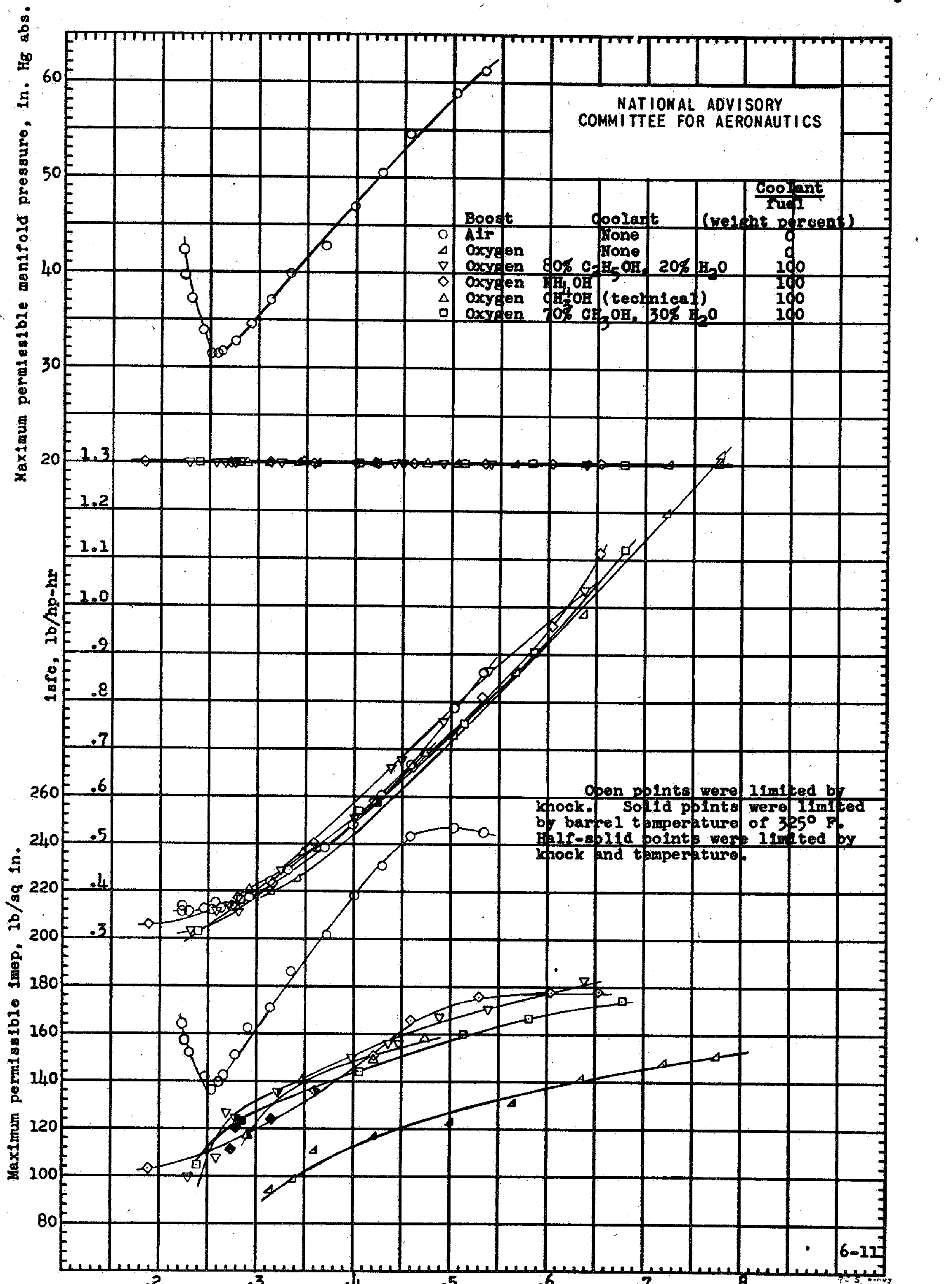

Figure 5. - Engine performance with oxygen boost in conjunction with different internal coolants. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm, spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

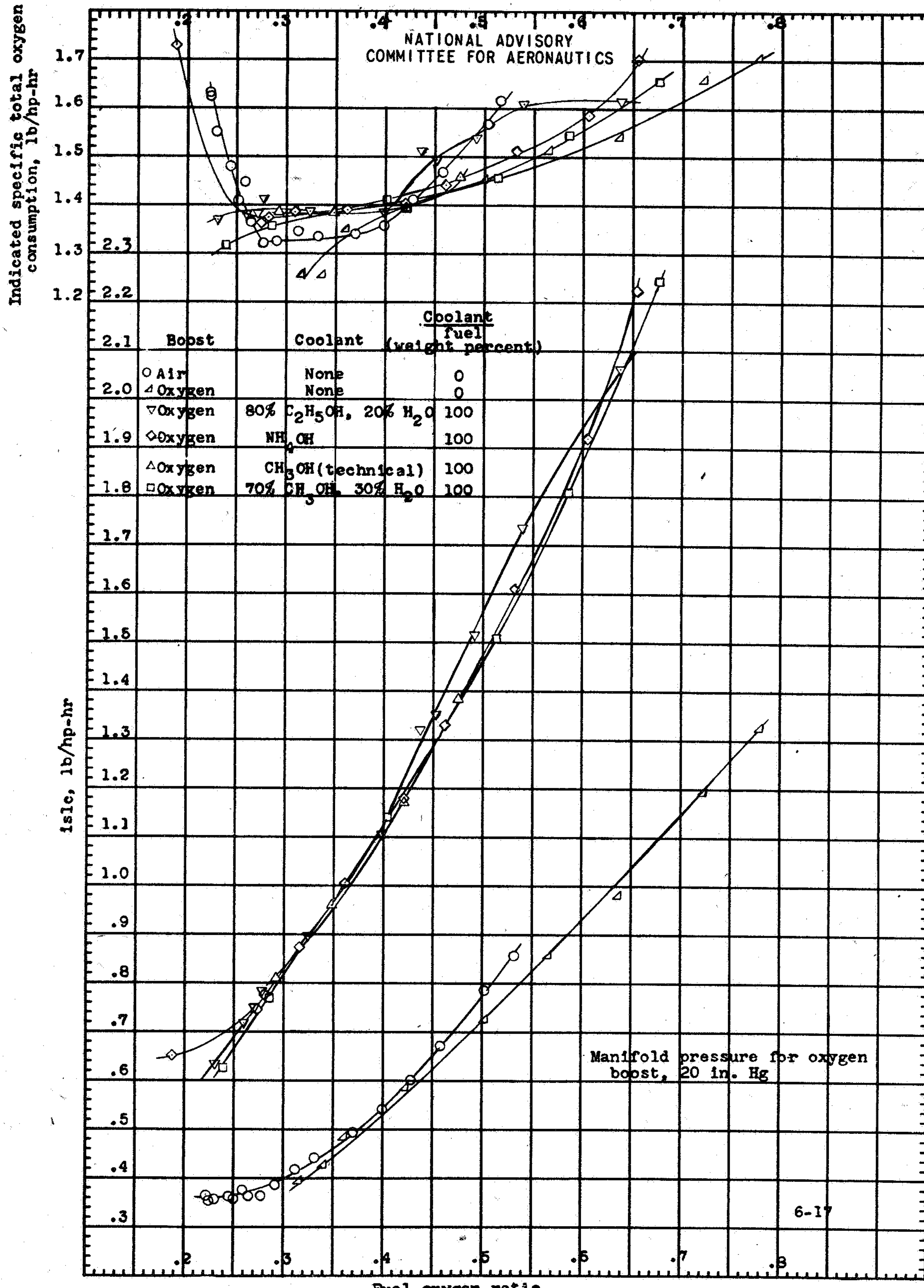

Figure 6. - Indicated specific liquid consumption and indicated specific total oxygen consumption for oxygen boost in conjunction with different internal coolants. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

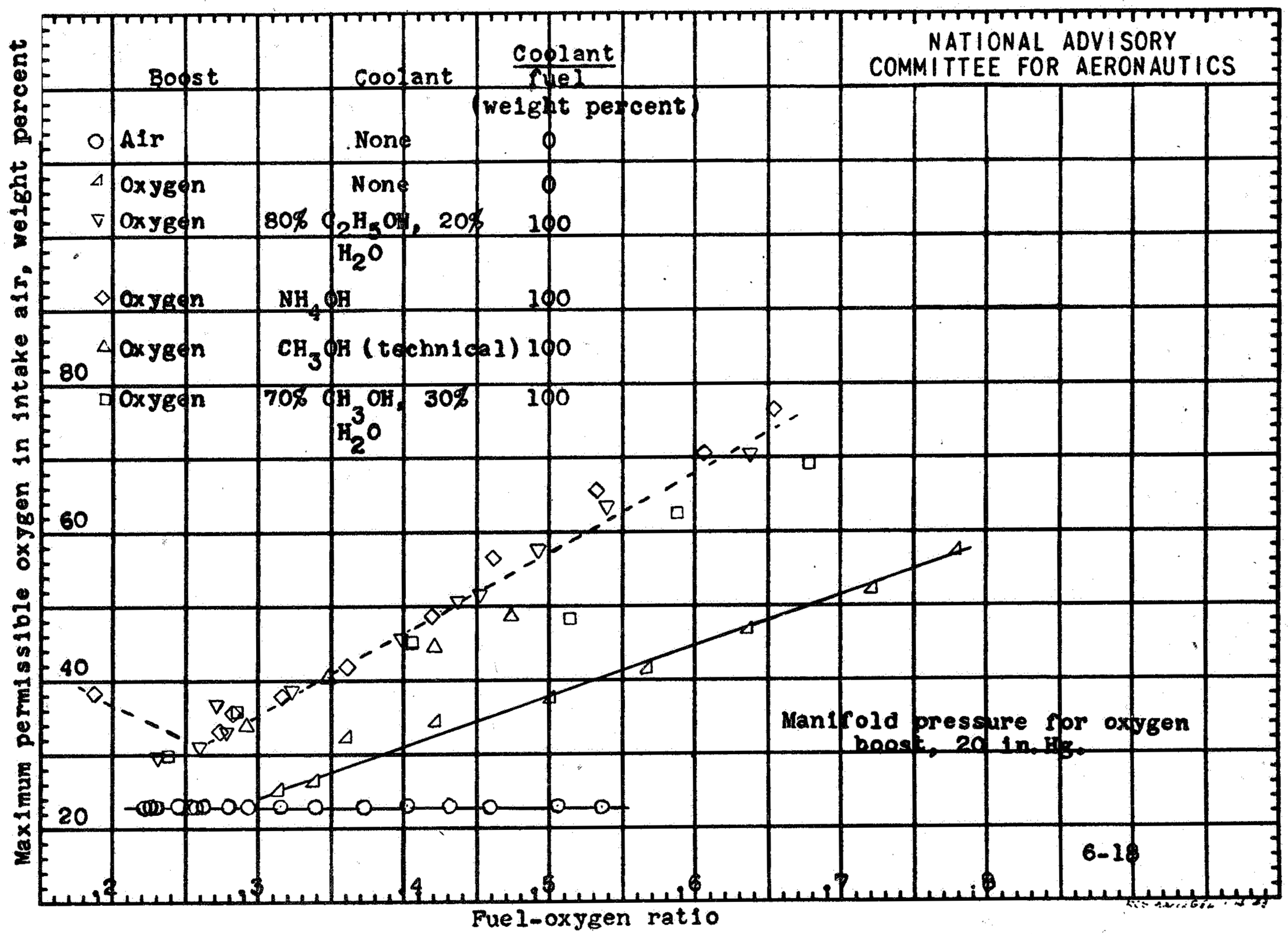

Figure 7. - Maximum permissible percentage of oxygen in intake air with different coolants. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

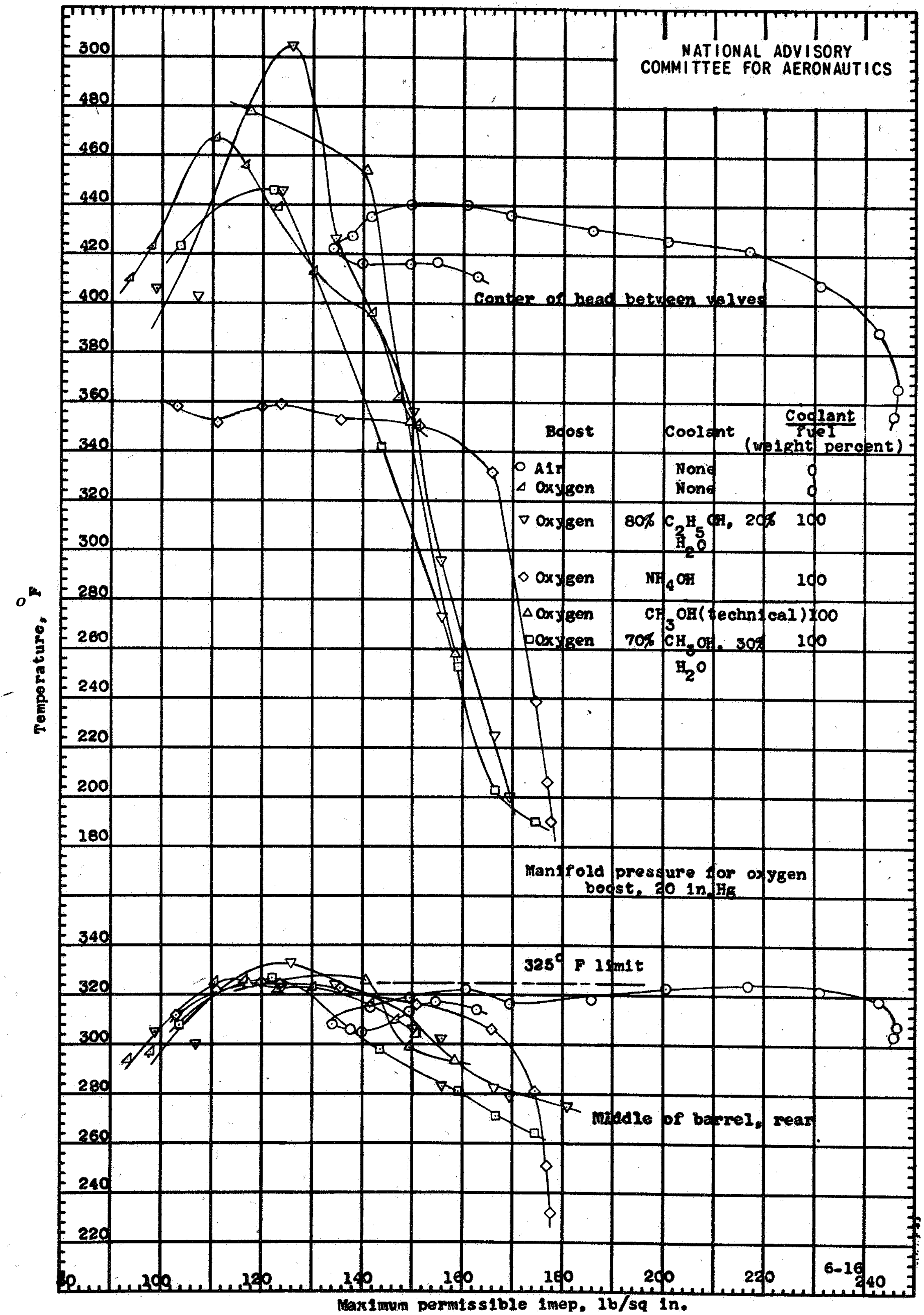

Figure 8. - Engine temperatures at maximum permissible performance with oxygen boost in conjunction with different internal coolants. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

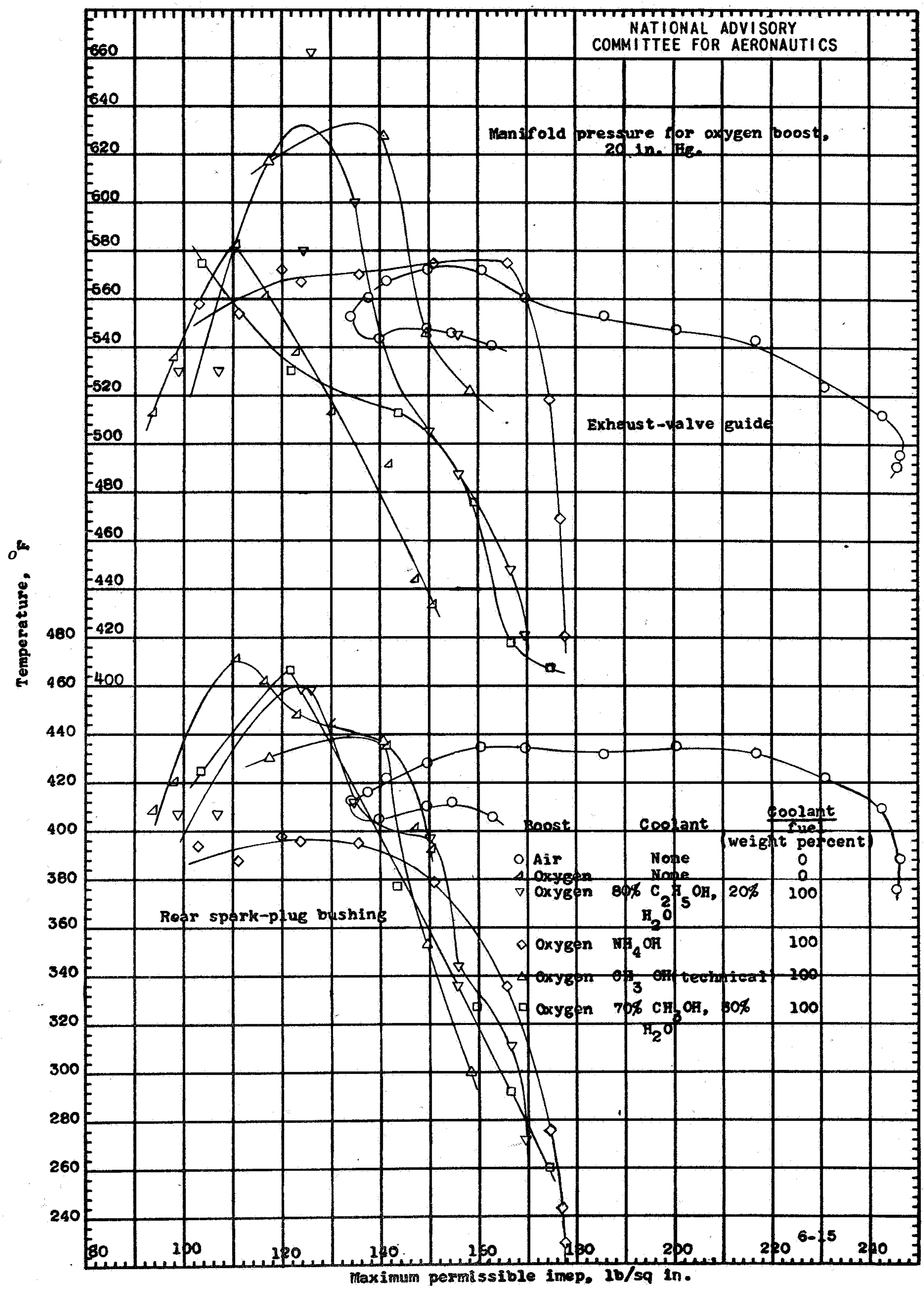

Figure 8. - Concluded.

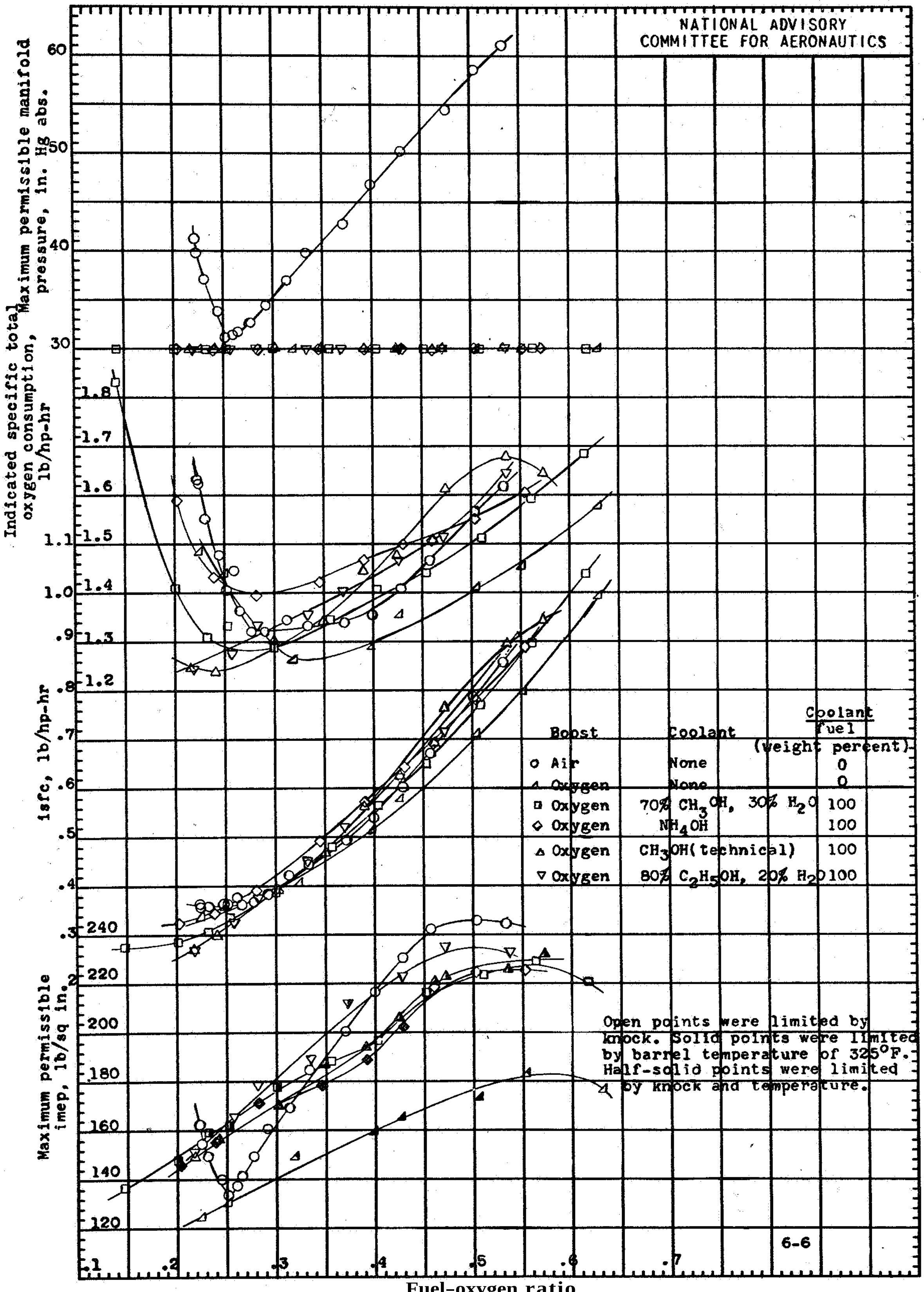

Figure 9. - Engine performance with oxygen boost in conjunction with different internal coolants. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C. ; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

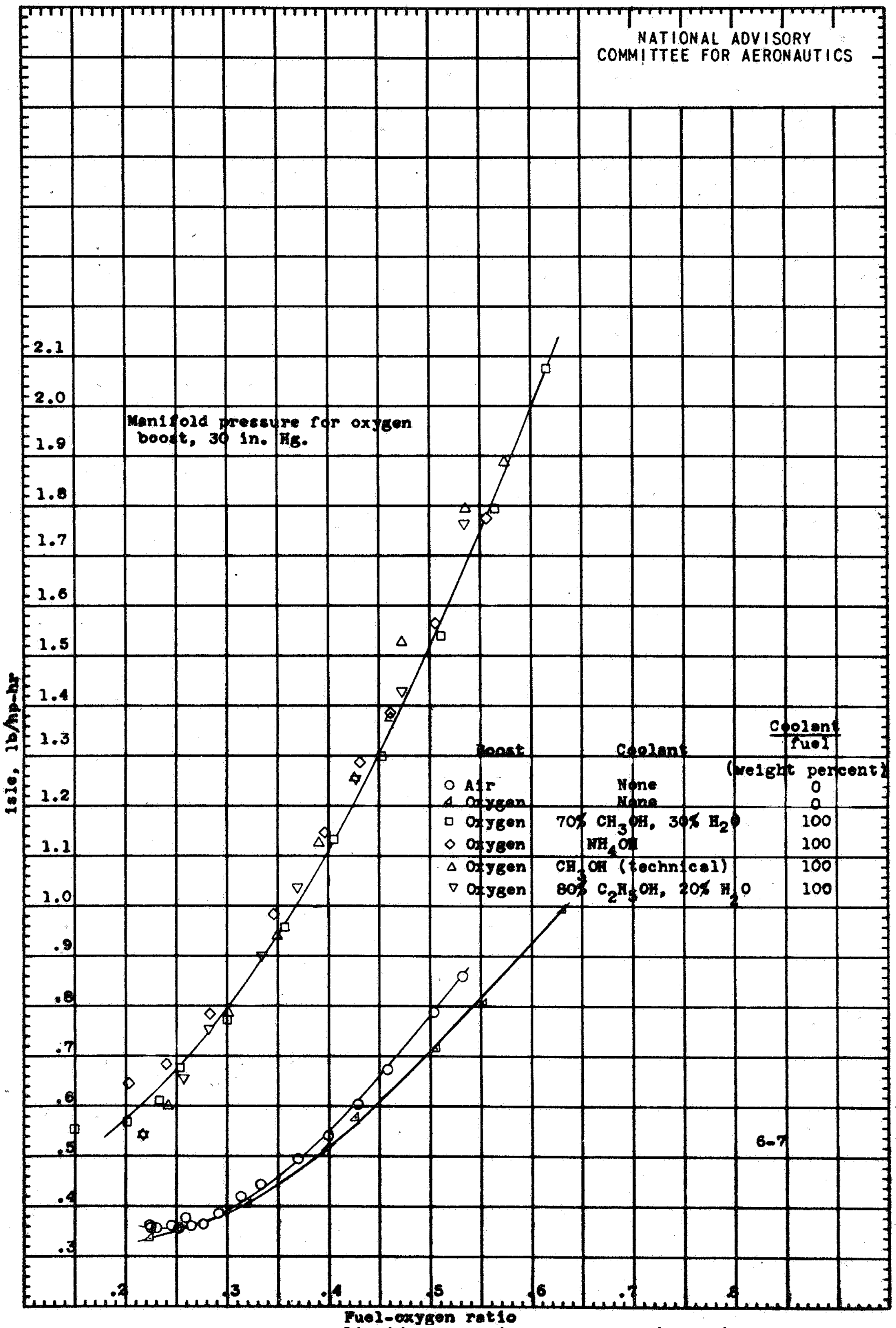

Figure 10. - Indicated specific liquid consumption with oxygen boost in conjunction with different internal coolants. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

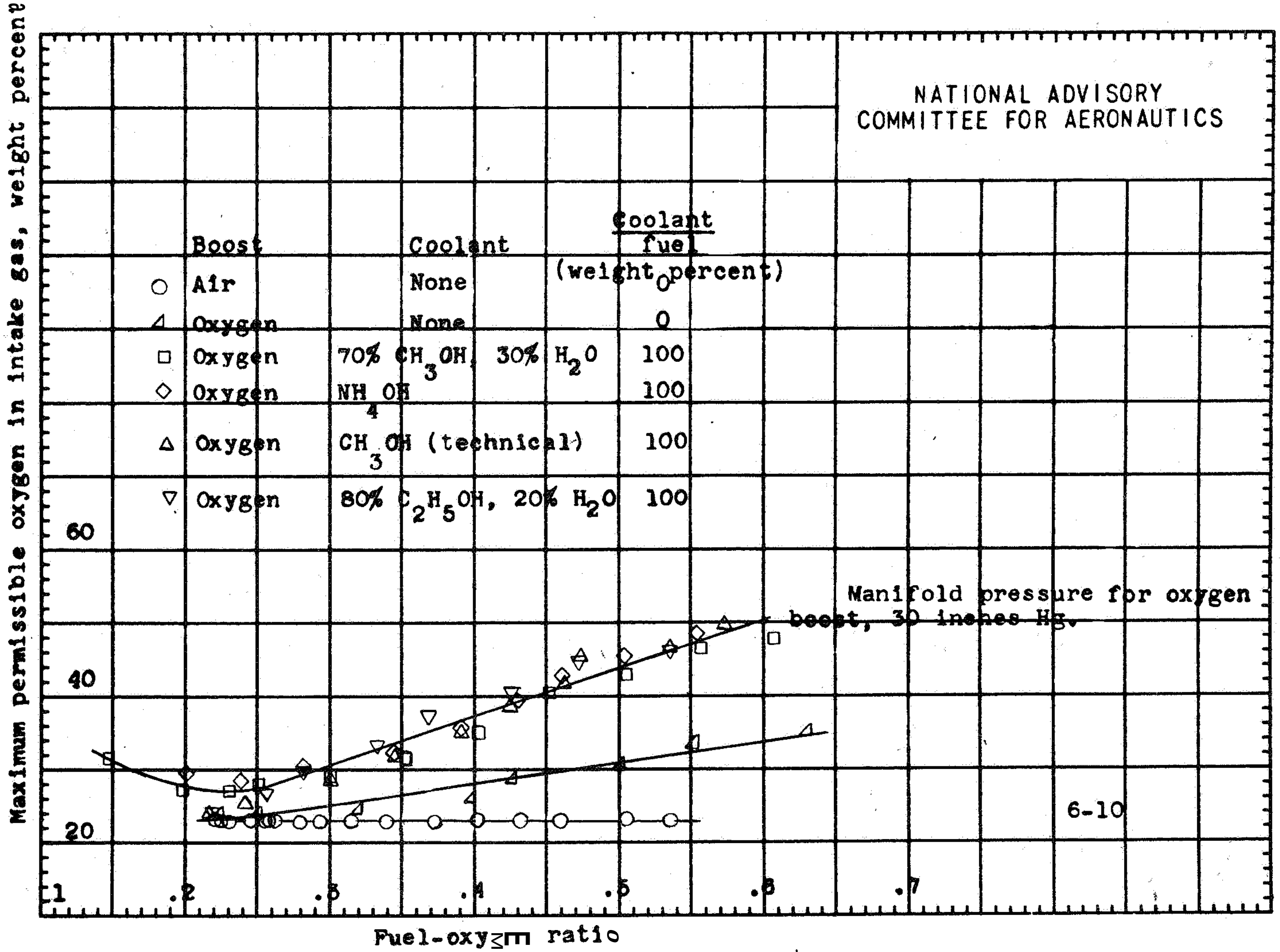

Figure 11. - Maximum permissible percentage of oxygen in intake gas with different internal coolants. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

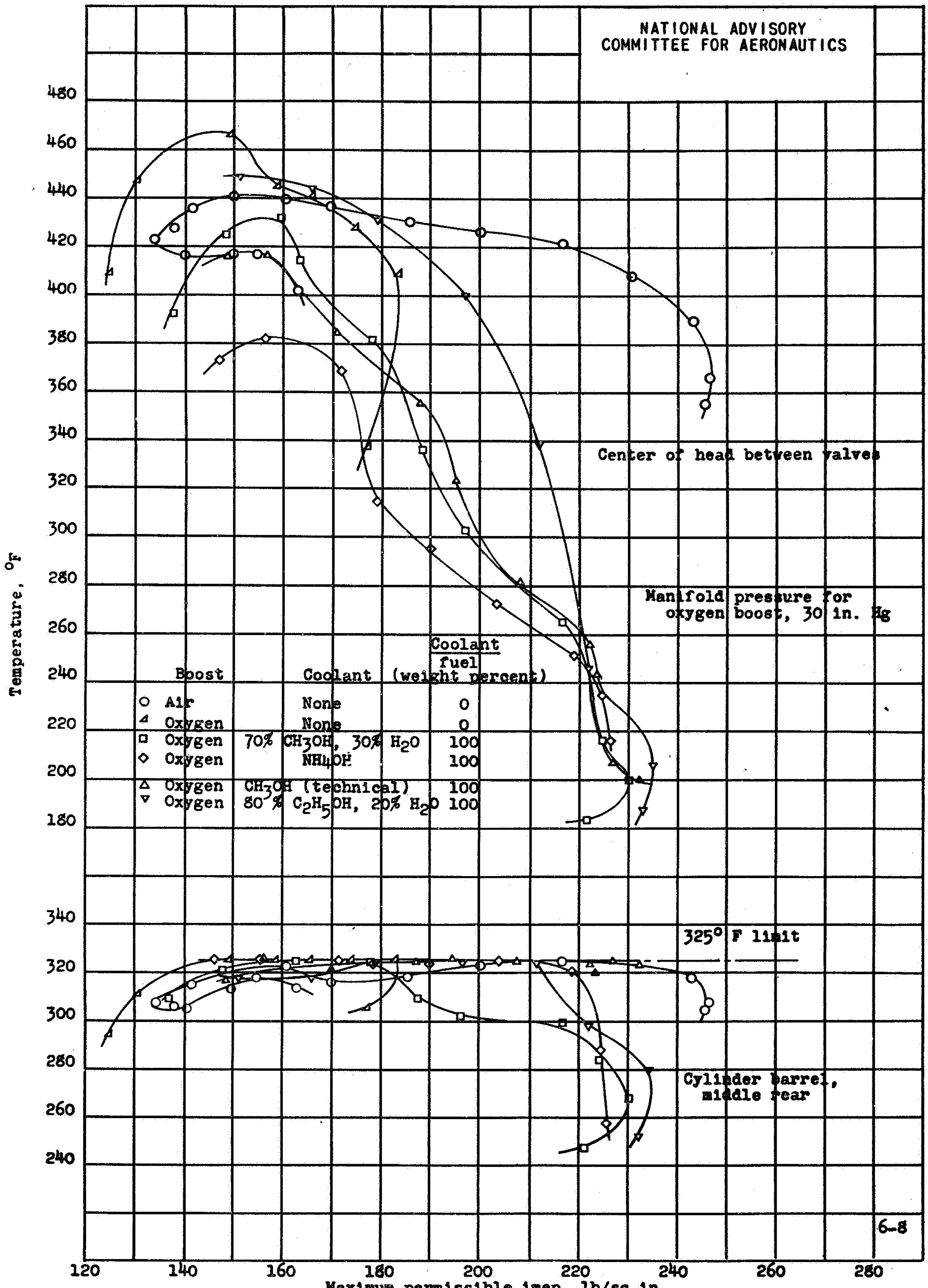

Figure 12. - Engine temperatures at maximum permissible performance with oxygen boost in conjunction with different internal coolants. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

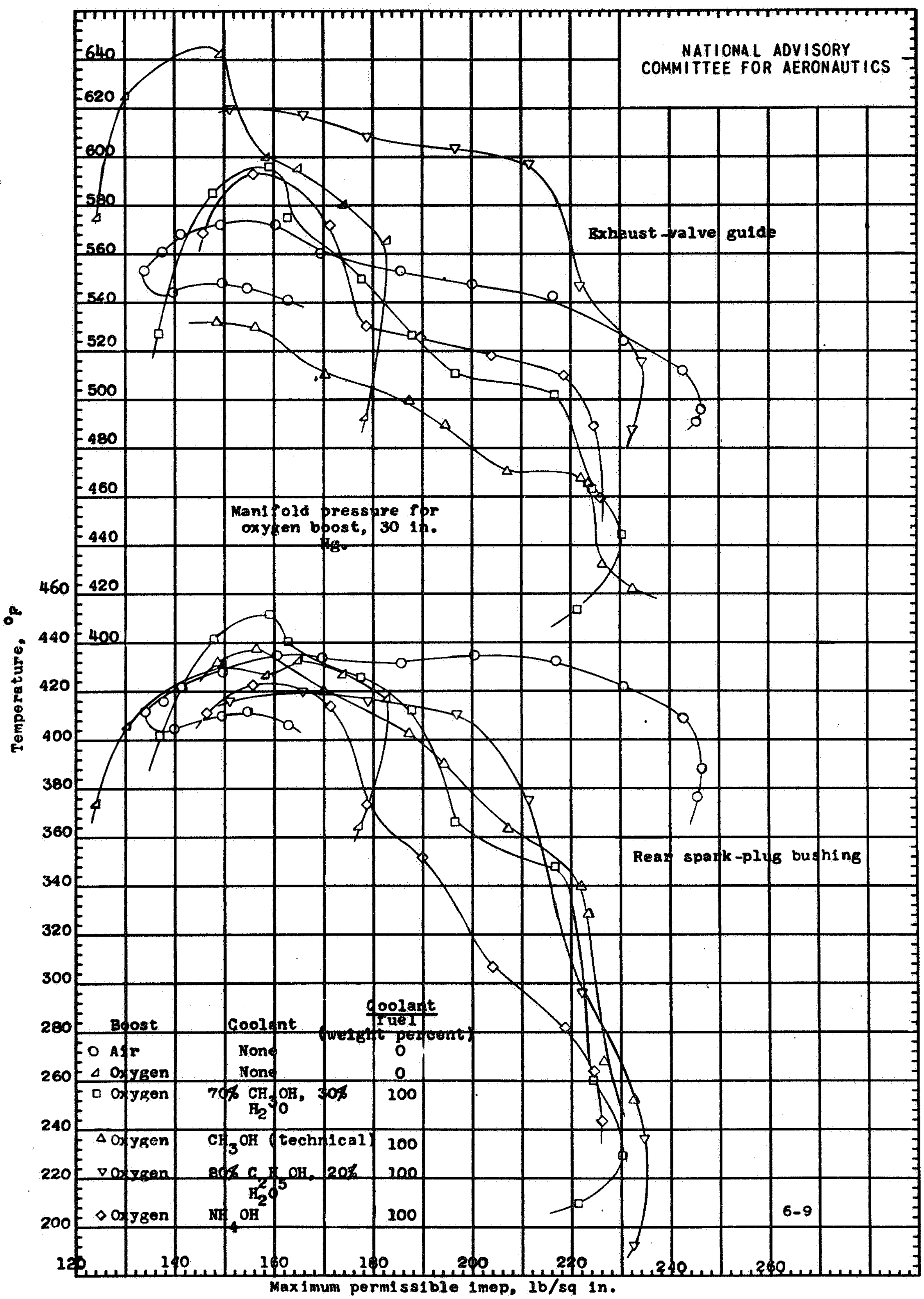

Figure 12. - Concluded.

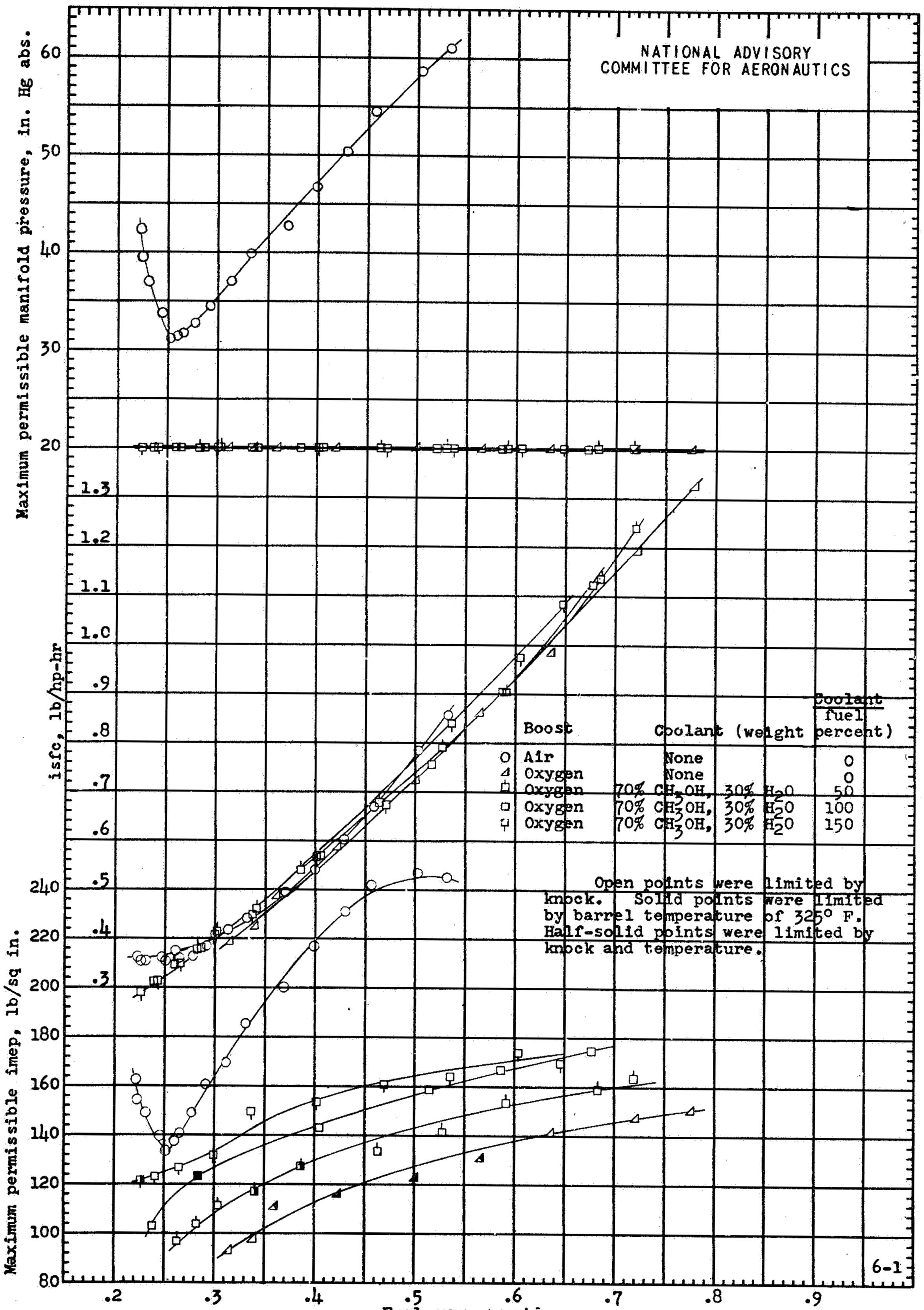

Figure 13. - Engine performance with air boost and with oxygen boost in conjunction with various amounts of internal coolant. Internal coolant, 70 percent methyl alcohol, 30 percent water; Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

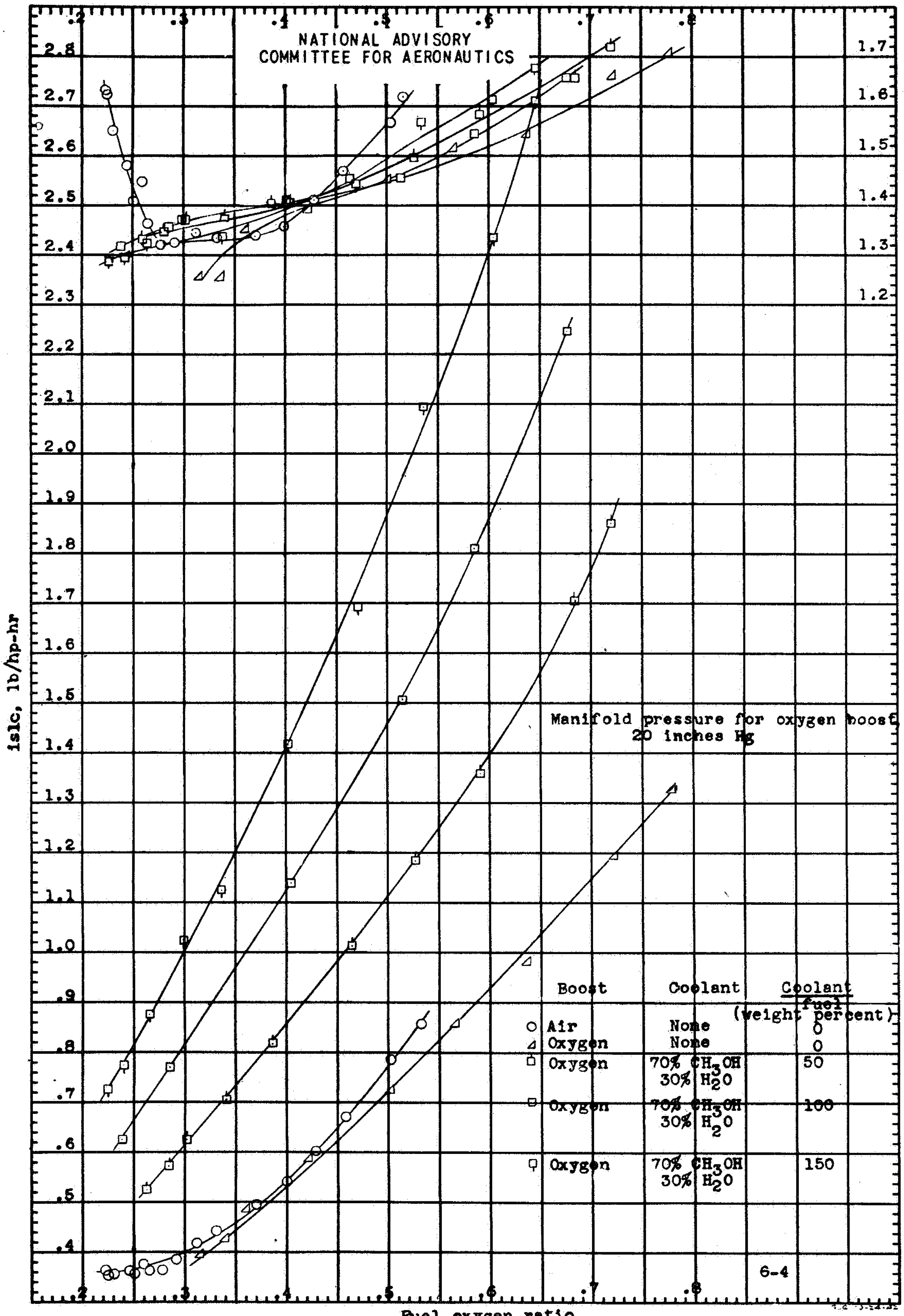

Figure 14.- Indicated specific liquid consumption and indicated specific total oxygen consumption with air boost and with oxygen boost in conjunction with various amounts of internal coolant. Internal coolant, 70 percent methyl alcohol, 30 percent water; Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

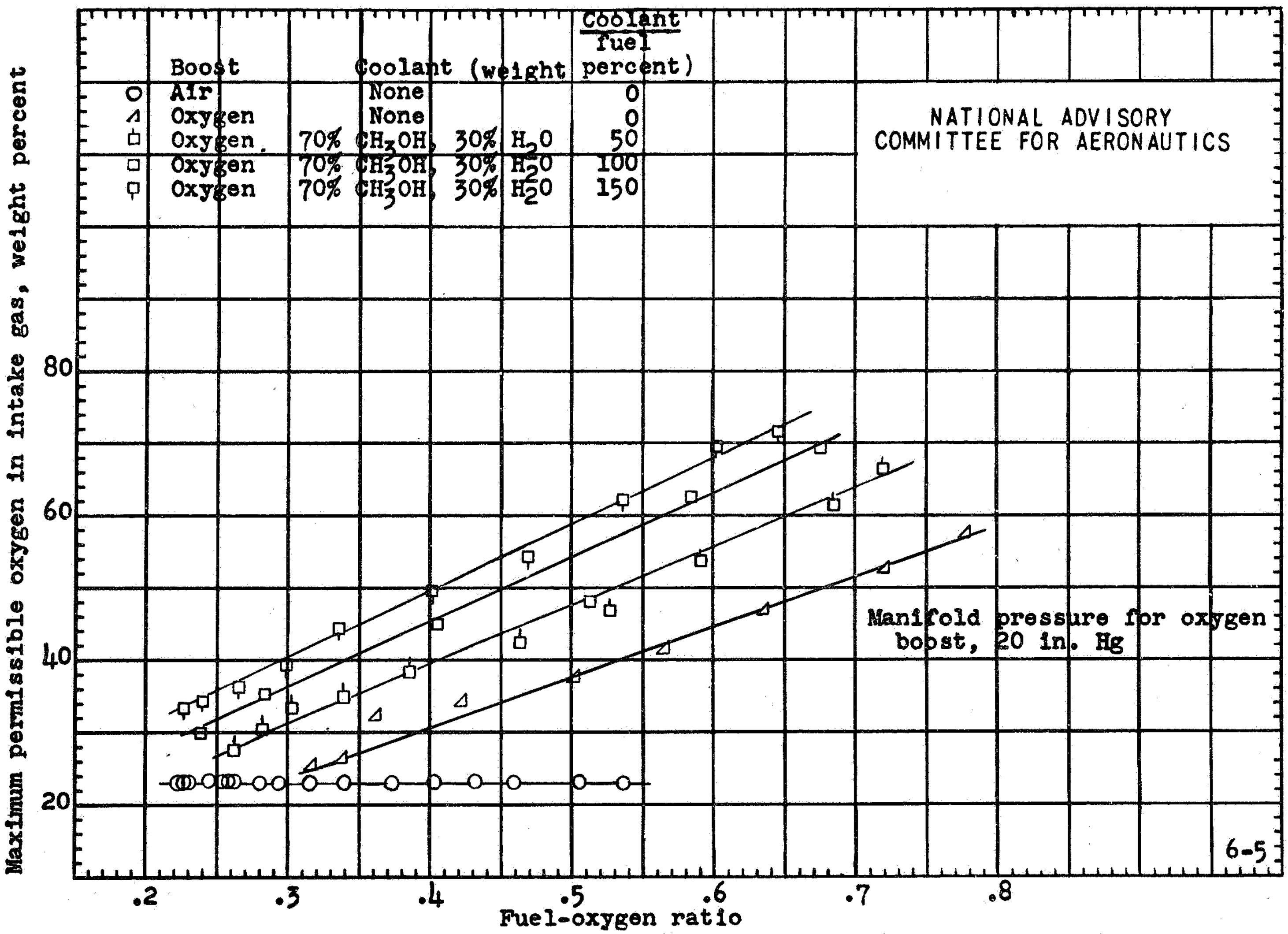

Figure 15. - Maximum permissible percentage of oxygen in intake gas with various amounts of internal coolant. Internal coolant, 70 percent methyl alcohol, 30 percent water; Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

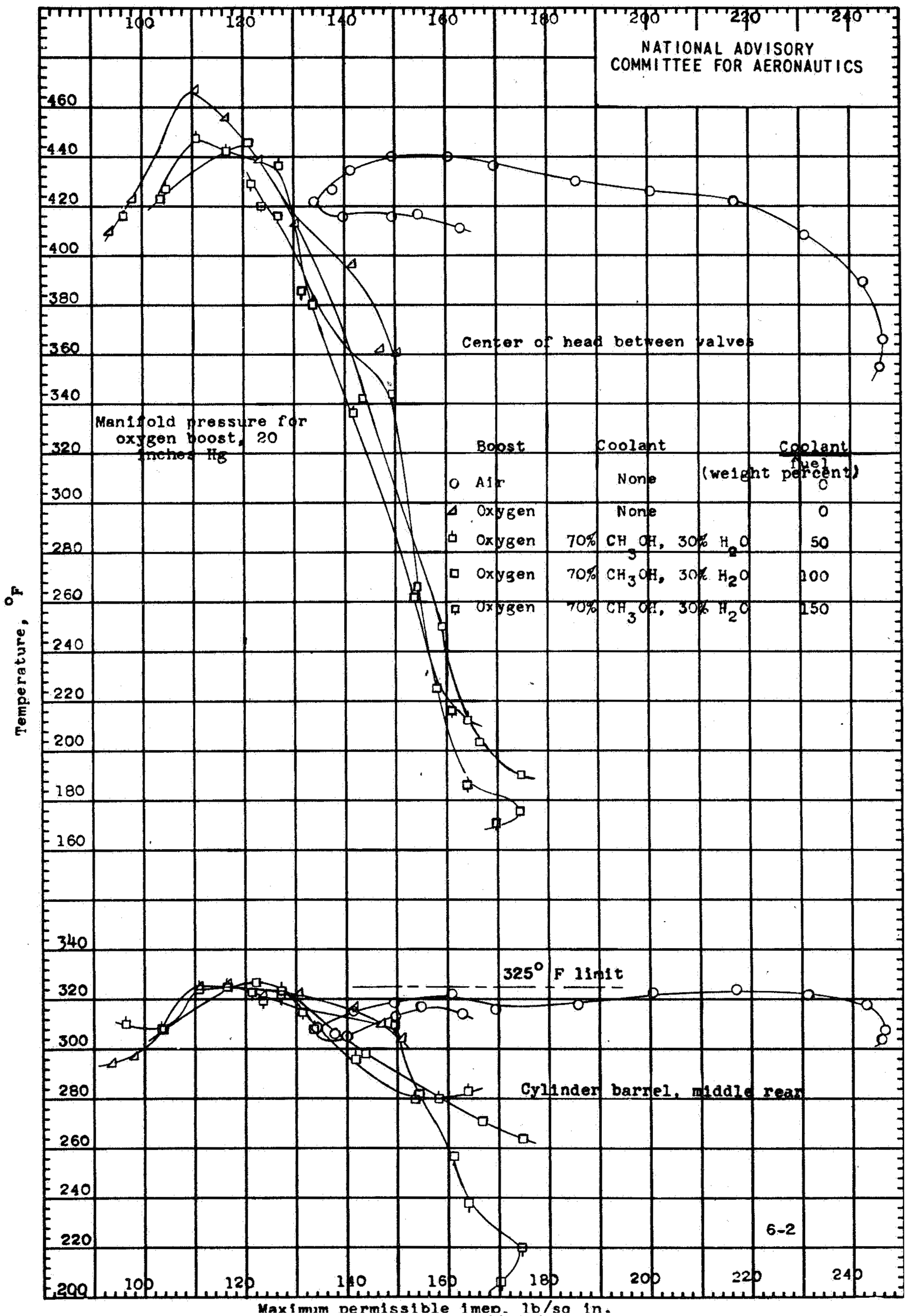

Figure 16. - Engine temperatures at maximum permissible performance with air boost and with oxygen boost in conjunction with various amounts of internal coolant. Internal coolant, 70 percent methyl alcohol, 30 percent water; Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

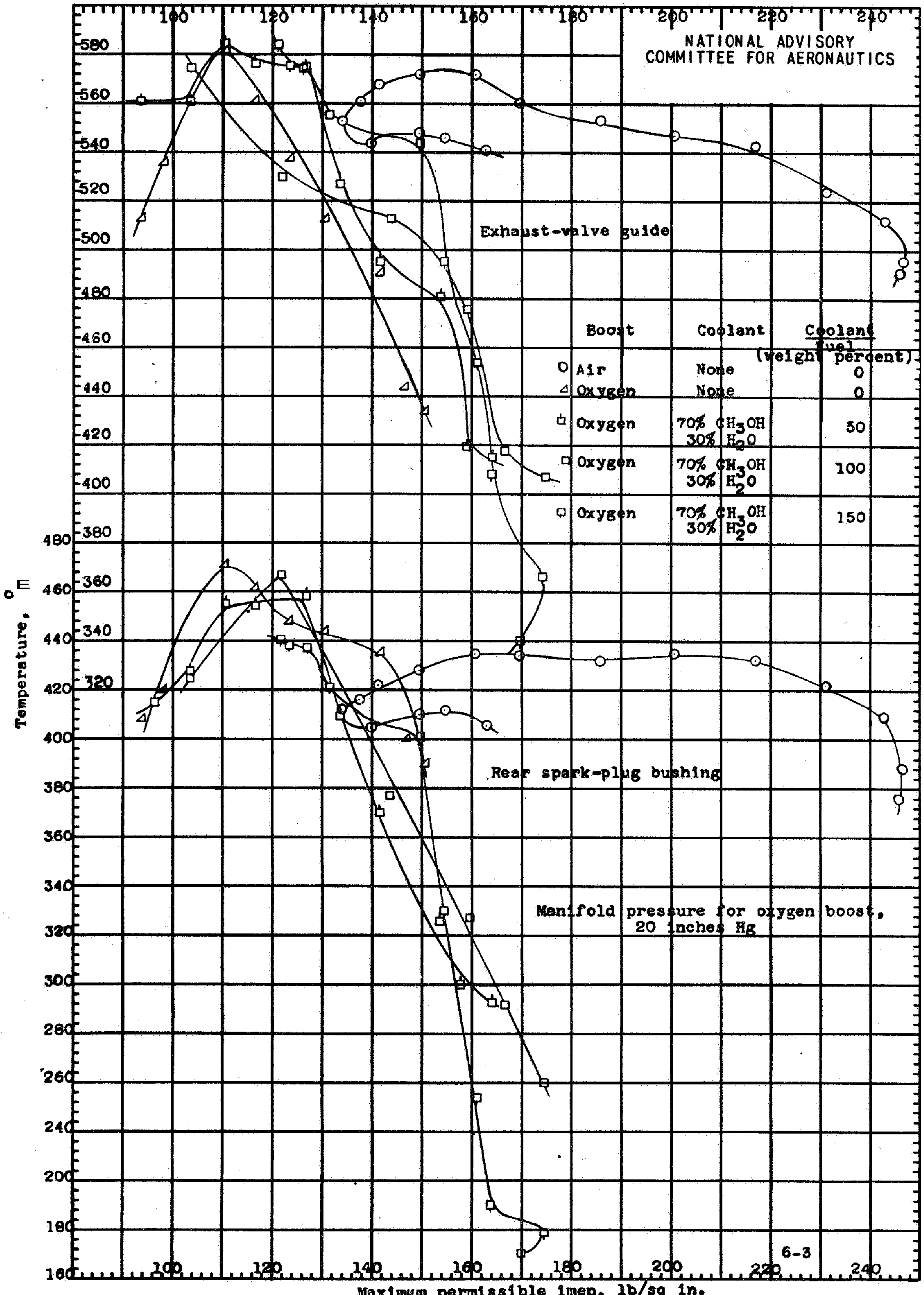

Figure 16. - Concluded.

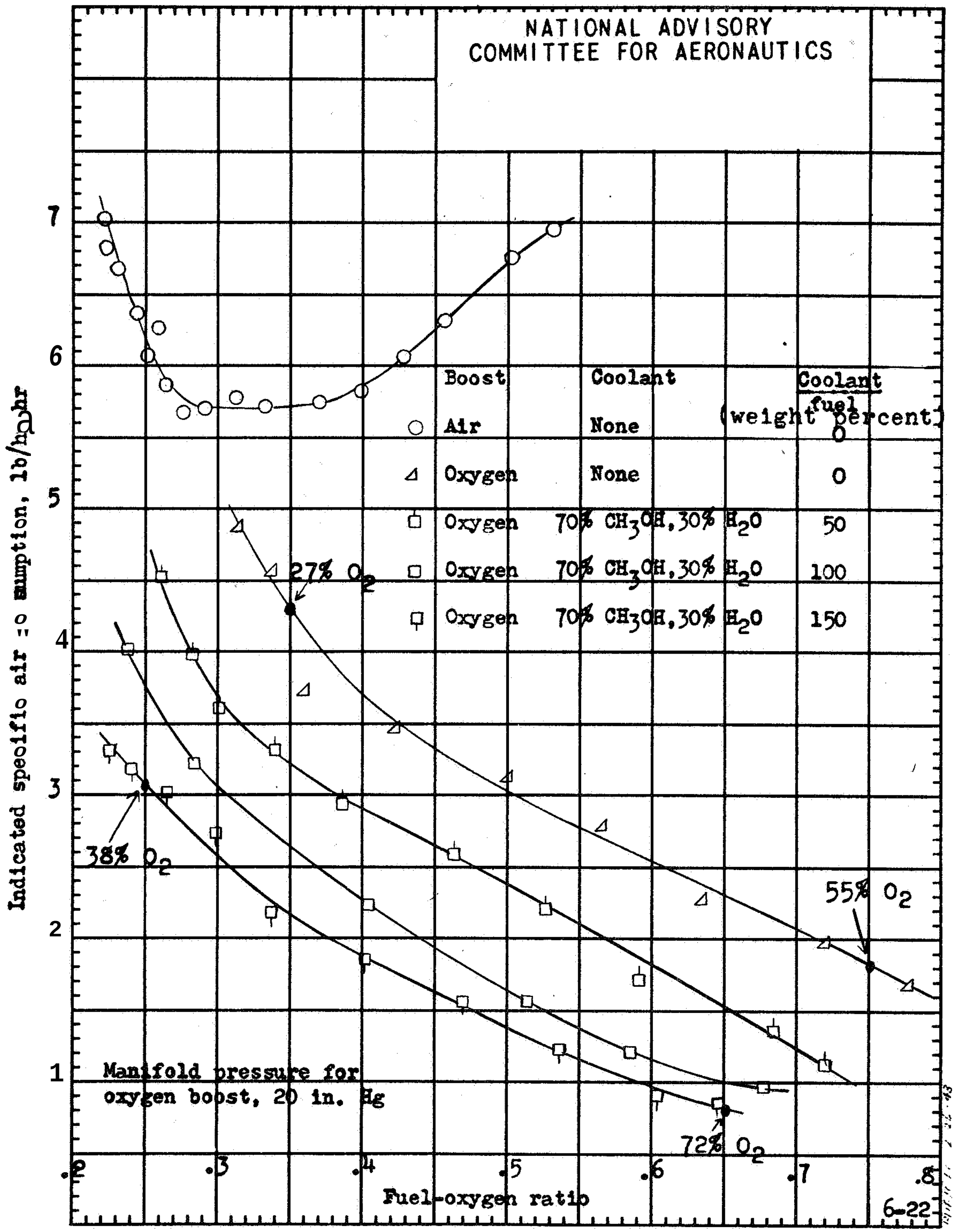

Figure 17. - Indicated specific air consumption with air boost and with oxygen boost in conjunction with various amounts of internal coolant. Internal coolant, 70 percent methyl alcohol, 30 percent water. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

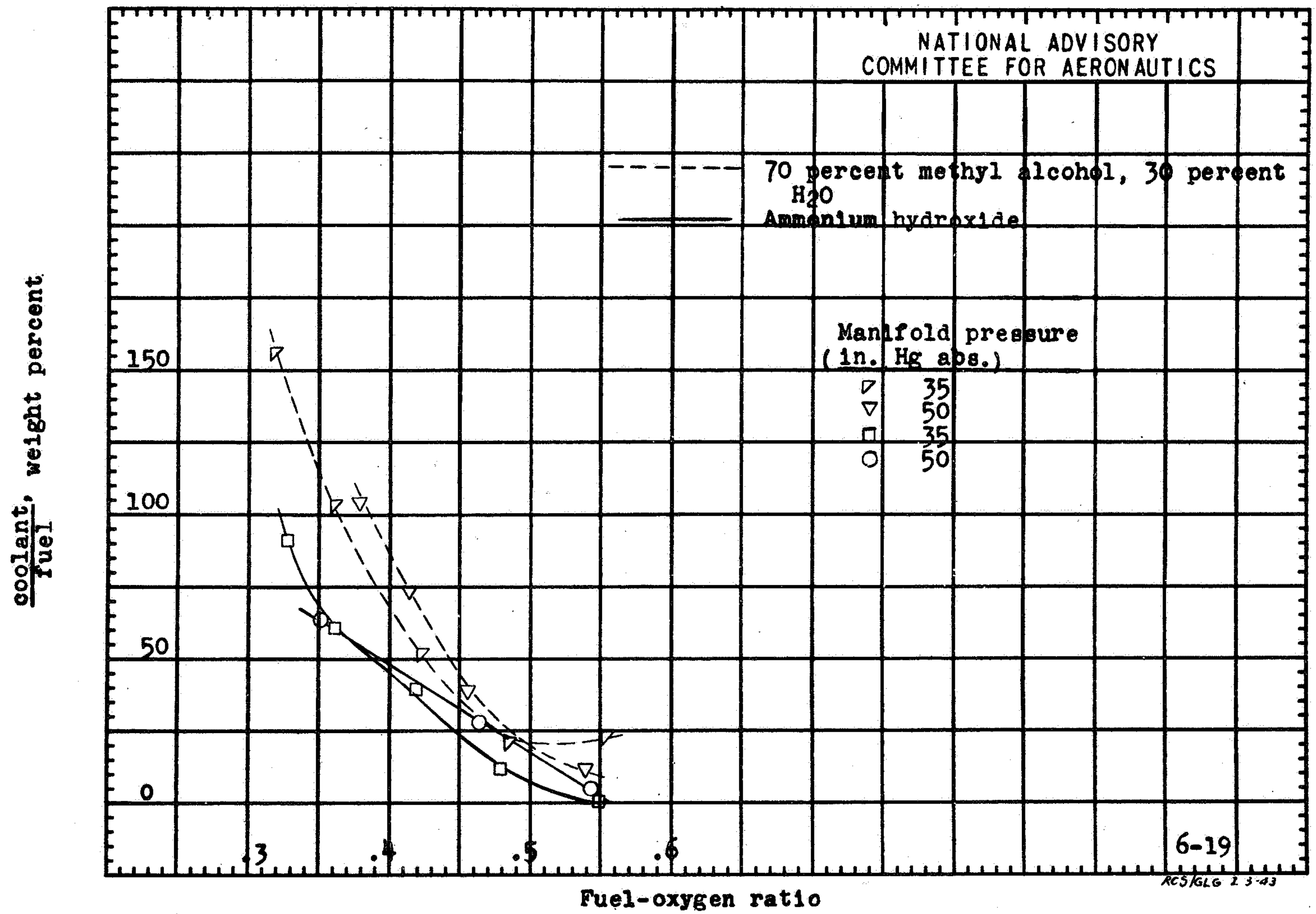

Figure 18. - Ratio of coolant to fuel for 10-percent drop in power at different manifold pressures. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air pressure drop across cowling, 10 inches of water; cooling-air upstream temperature, 125° F; fuel, Army 100-octane aviation gasoline.

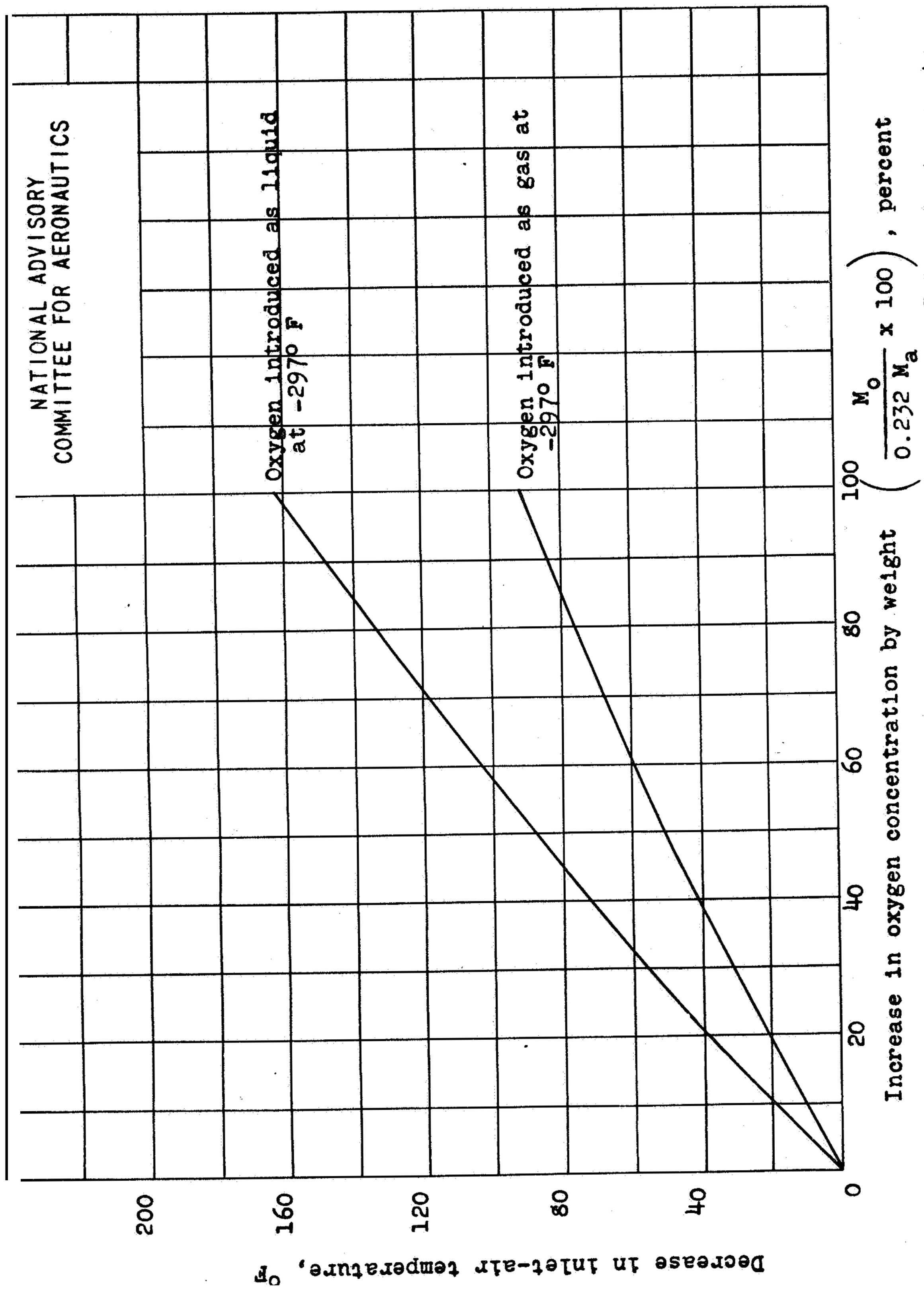

Figure 19. - Cooling effect when oxygen is added to the inlet air. Inlet-air temperature, 212° F.

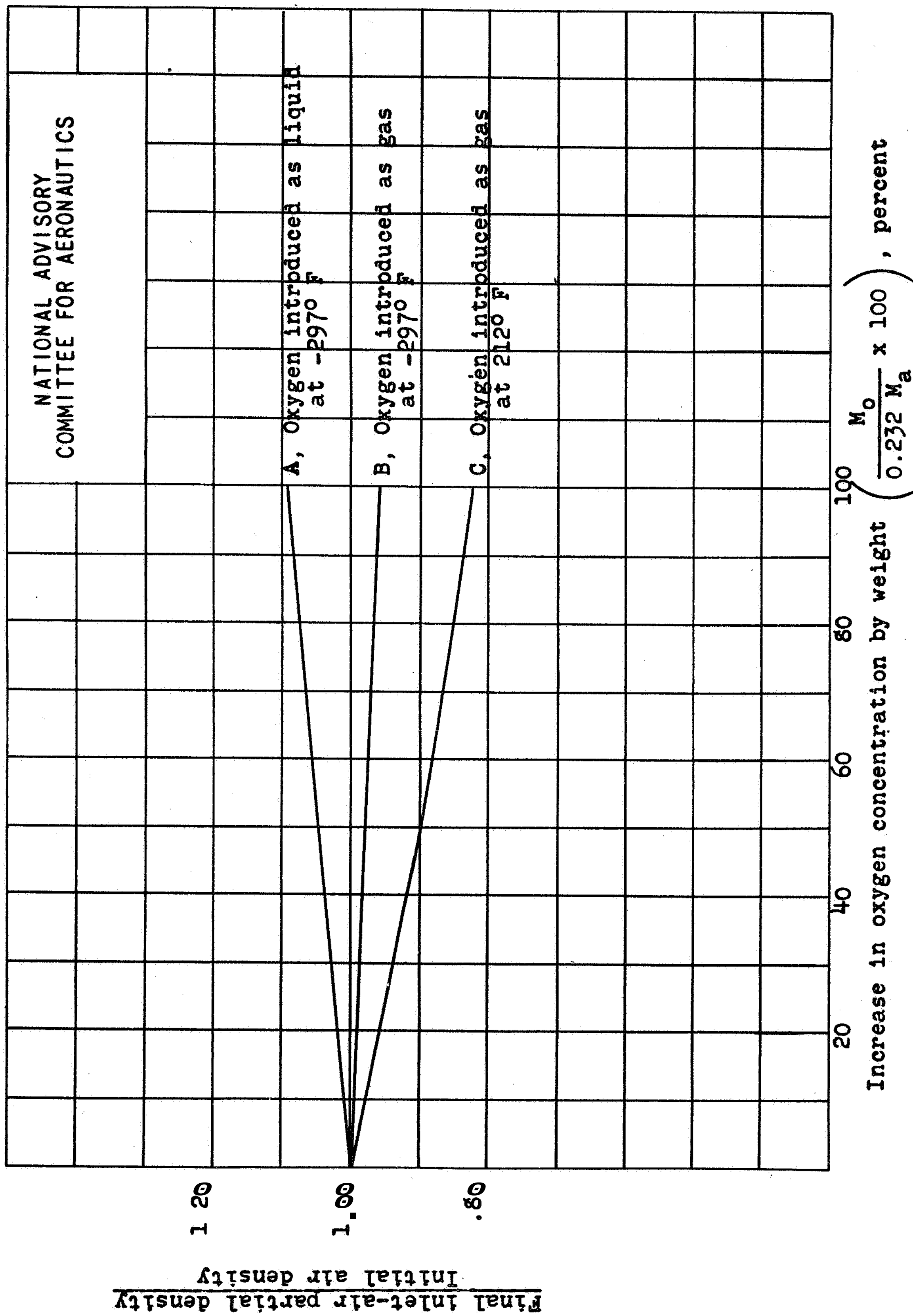

Figure 20. - Relative inlet-air densities after oxygen is added. Inlet-air temperature, 212° F; manifold pressure assumed constant.

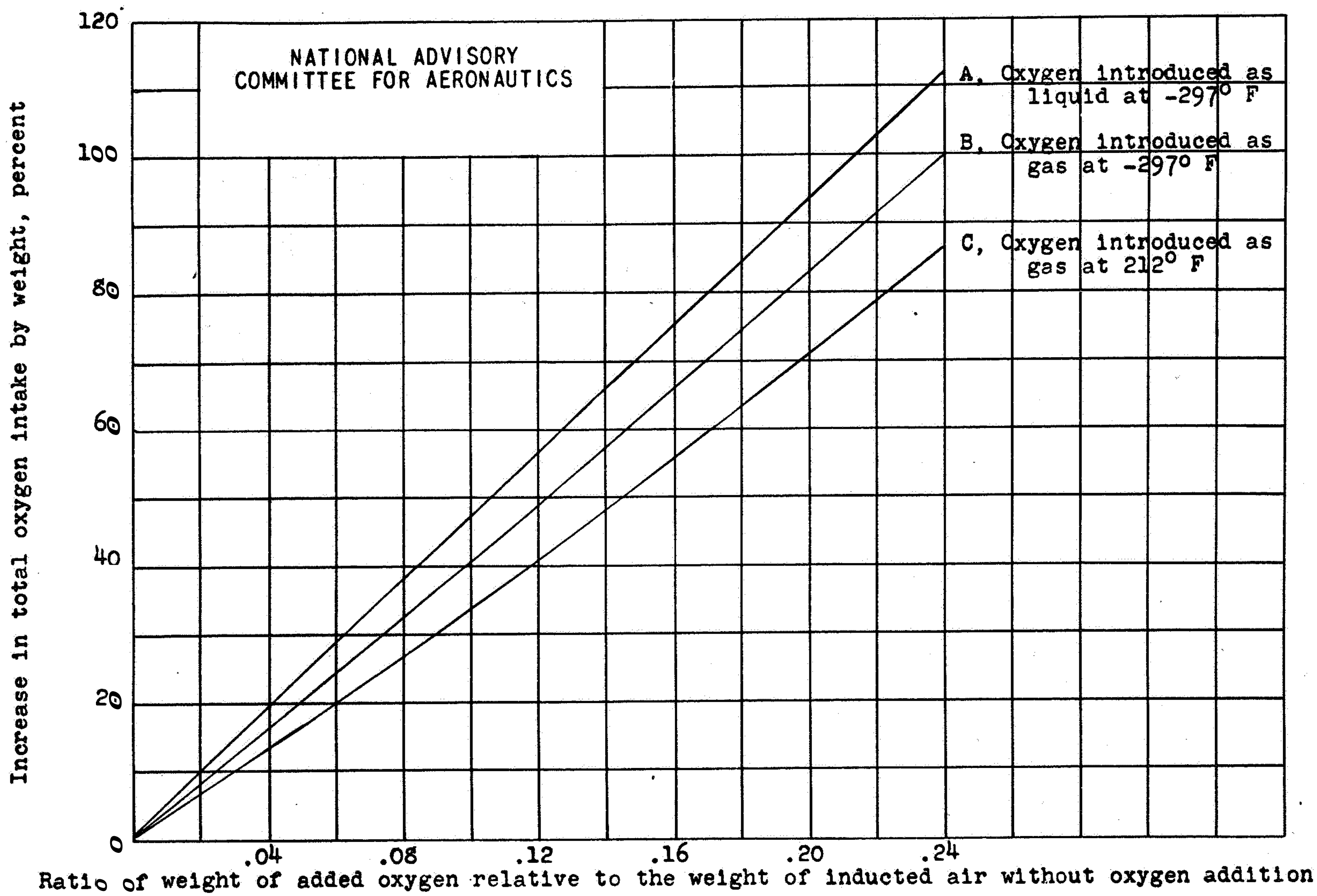

Figure 21. - Increase of total oxygen inducted, relative to air without additive oxygen, as additive oxygen is increased. Inlet-air temperature, 212° F; manifold pressure assumed constant.